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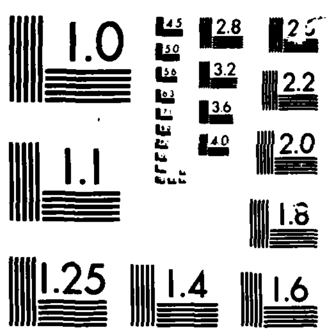

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Results of Year 3 are presented and includes: (a) a detailed report on the quantitative analysis of practice effects upon the triphasic EMG pattern for a maximum speed forearm flexion movement; (b) patterned electrical stimulation effects upon neuromotor coordination mechanisms underlying speed of forearm flexion movement speed; and (c) high frequency Russian type electrical stimulation of agonist and antagonist muscle groups involved in fast forearm flexion movement.

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APPENDIX B

Patterned Electrical Stimulation Effects Upon
Neuromuscular Coordination Control Mechanisms
Underlying Speed of Forearm Flexion Movement

PROCEDURES

Description of the sample studied, the informed consent document, and the sample size estimation, compose this first section. Thereafter, the movement, movement apparatus, the parameters and their selection, the measurement techniques, and the testing schedule and procedures are discussed.

Subjects

University of Massachusetts students in Amherst were recruited for in this study. The total ensemble of subjects, regardless of sex, was equally divided into two control groups

1-A

and four functional electrical stimulation groups to be described below.

Informed Consent Document

In accordance with the general guide lines on the rights and welfare of human subjects approved by the Faculty Senate of the University of Massachusetts in Amherst, an informed consent document was presented to every subject. Each subject was asked first to read carefully and then sign the said document, and have clearance from the health services, in order to participate in the study.

Sample Size Estimation

This study proposes principally to address the two following questions: (1) What are the effects of the functional electrical stimulation treatments upon the neuromuscular coordination control mechanisms; and (2) What are the effects of different functional electrical stimulation treatment conditions. Therefore, two different sample size estimation analyses are

presented.

Treatment effects sample size estimation

This sample size was executed in order to identify the adequate sample size required to test accurately for the functional electrical stimulation treatment effects over time. The performance criterion, movement time, was utilized to perform the sample size estimation analysis. Lagasse (1975) reported a maximum speed forearm flexion movement time mean and standard deviation of 150 and 13 milliseconds respectively. An intraclass correlation coefficient of 0.88 was also reported. Therefore, considering an effect size of 10 percent, or 15 milliseconds, a 0.05 confidence level, R=0.88, and a power of 80 percent, this pre-experimental sample size estimation analysis yielded a sample size of 6 subjects (see Appendix B).

Treatment condition effects sample size estimation

This sample size estimation was conducted in order to identify the sample size required to assess different treatment condition effects. Here again, movement time was utilized as the sample size estimation criterion. The same mean and standard deviation were utilized (X = 150 ms and SD = 13 ms). However, in this specific case the treatment conditions represented

independent groups, and therefore, the correlation coefficient could not be taken into account. The sample size was then established at 12 subjects per group for a power of 80 percent, and at 6 subjects per group for a power of 50 percent (see Appendix B).

The Experimental Movement

The right arm maximum speed forearm flexion movement was utilized for this investigation. This movement was selected based upon a literature review and because it fulfills movement characteristics recognized as important in the selection of experimental movements (Wilkie, 1950). The movement characteristics are the following: the elbow is a uni-axial joint, a limited number of muscles are involved in its execution, and it can be executed without participation of any other body segments. This experimental movement is executed against gravity; however, Kilmer et al. (1982) demonstrated through mathematical modelling that gravity played a negligible role in the execution of such a maximum speed forearm flexion movement, and was therefore overlooked in the discussion of the results.

To insure standardization in the execution of the maximum

speed forearm flexion movement, the subjects' right hand was secured in a semiprone position. As seen on Figure 1, before onset of the movement the forearm of the subject was resting at a 15 degree angle. The maximum speed forearm flexion movement then consisted of a maximum speed forearm flexion from the 15 degree resting position to a 90 degree target along the sagittal plane; i.e. 75 degrees range of motion. Therefore, the subject was asked to stop volitionally the maximum speed forearm flexion movement on the 90 degree target as accurately as possible. Thus, the movement described herein represent a class B movement. Bailey and Presgrave (1958) categorized experimental movements into two different classes. Class A movements are stopped by an external force, and class B movements are voluntarily stopped by antagonistic muscle forces.

Experimental Movement Apparatus

A specially designed apparatus was utilized in order to isolate and standardize the maximum speed forearm flexion movement, and also to allow assessment of the experimental parameters to be described below. As illustrated in Figure 1, the subject was seated on an adjustable stool with the chest strapped against a chest rest attached to the specially designed apparatus in order to minimize unwanted synergistic movements.

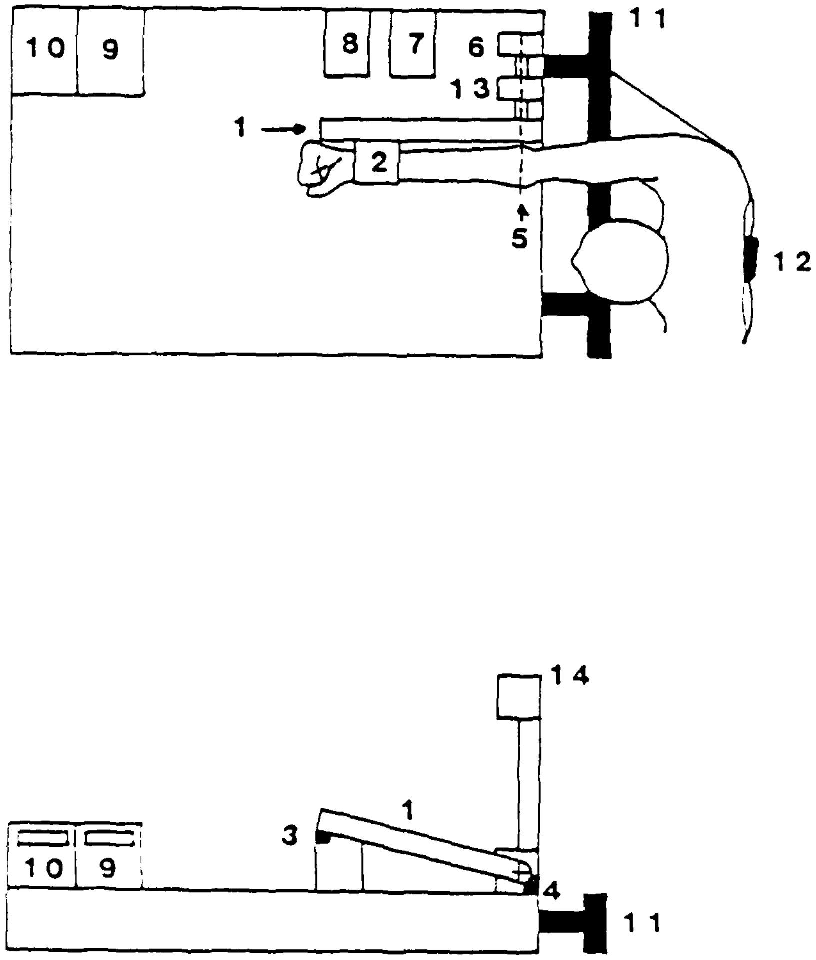

Figure 1. Experimental movement apparatus. (1) wooden bar; (2) wrist cuff; (3) onset microswitch; (4) target microswitch; (5) rotation axis; (6) potentiometer; (7) analog signal differentiator; (8) event marker integrated circuit; (9) movement time millisecond timer; (10) time of positive acceleration millisecond timer; (11) chest pad; (12) seat belt; (13) ball bearing joint; (14) 90 degree target.

The stool height was adjusted so that the subject's right upper arm rested on the apparatus approximately parallel to the floor. The right forearm of the subjects was secured to a wooden bar by a leather cuff. The wooden bar was allowed to rotate freely around an axis which coincides with the elbow joint center of rotation. The wooden bar center of rotation is attached to a potentiometer enabling assessment of the forearm angular displacement. As mentioned above, before onset of the maximum speed forearm flexion movement, the forearm attached to the wooden bar rested on a microswitch at a 15 degree angle with the horizontal. Upon onset of the maximum speed forearm flexion movement, the microswitch was triggered which activated a millisecond timer (Lafayette Instrument Corporation, model 54419). The latter was stopped when a second microswitch was activated by the wooden bar crossing the 90 degree target.

On every trial the subject was asked to execute the maximum speed forearm flexion movement immediately following verbal commands by the experimenter, and stop the movement as close as possible to the 90 degree target.

Parameter Selection

On each trial of every testing day for every subject three types of information was recorded; i.e. kinematic, electromyographic and tension output. Angular displacement, velocity and acceleration represent the kinematic information monitored. The following kinematic parameters were derived from the kinematic information (see Figure 2 for schematic representation).

-Kinematic parameters

Movement time (K1): time elapsed between the onset of the maximum speed forearm flexion movement, from a 15 degree resting position, and the reaching of the 90 degree target.

Time of positive acceleration (K2): time spent by the forearm in the initial positive acceleration phase of the maximum speed forearm flexion movement.

Percent acceleration time (K3): time of positive acceleration expressed as a percent of movement time.

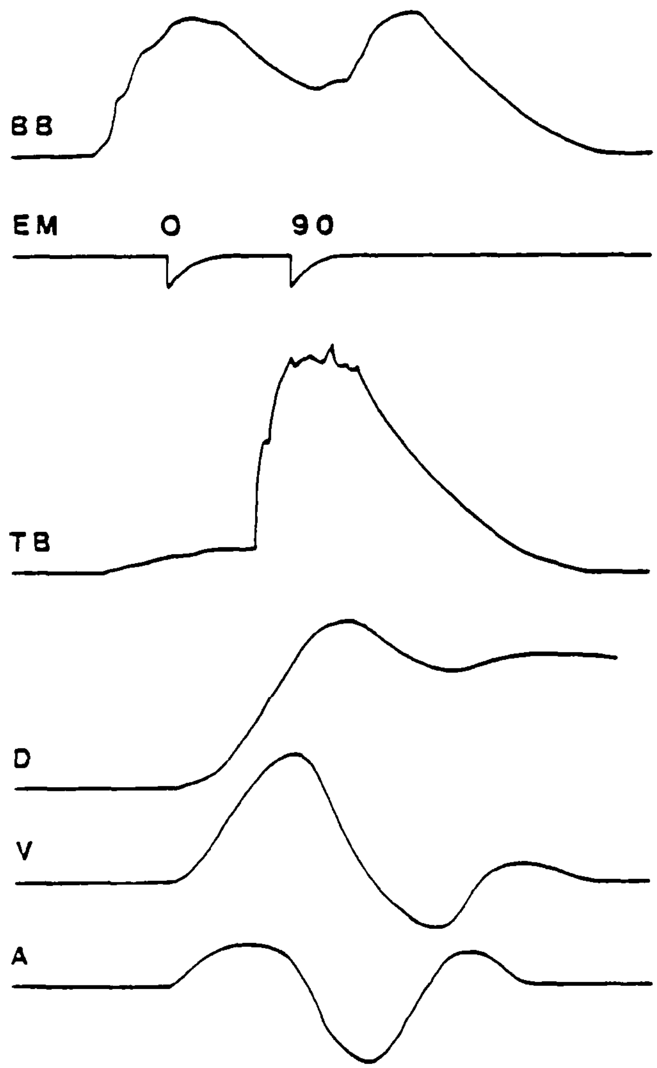

Figure 2. Schematic representation of the electromyographic pattern to be expected for a trial of the maximum speed forearm flexion movement. BB: biceps brachii integrated electromyography; EM: event markers; O: onset event marker; 90: 90 degree target event marker; TB: triceps brachii integrated electromyography; D: angular displacement; V: angular velocity; A: angular acceleration.

Maximum displacement (K4): peak angular displacement of the forearm during the execution of the maximum speed forearm flexion movement.

Time to maximum acceleration (K5): time elapsed between the onset of the maximum speed forearm flexion movement and the point of maximum or peak positive acceleration.

In other words, movement time represents the time required by a subject to execute the 75 degree maximum speed forearm flexion movement. Movement time was demonstrated to be a measurement of maximum speed of human movement (Lagasse, 1975). Furthermore, Fitts and Posner (1967) demonstrated that speed of human movement was independent of range of motion and, therefore, the selection of 75 degrees for the maximum speed forearm flexion movement range of motion does not require further substantiation. The kinematic parameters mentioned above were also found to represent objective measurements of neuromuscular coordination control mechanisms responsible for the control of speed of human movement. These neuromuscular coordination control mechanisms were shown to be independent of isometric force production and other neuromuscular coordination control mechanisms responsible for muscle contractions coordination (Boucher, 1980; Boucher and

Lagasse, 1980).

Surface integrated electromyography of the long head of the m. biceps brachii and the lateral head of the m. triceps brachii represent the electromyographic information recorded during the maximum speed forearm flexion movement trials. The expected electromyographic triphasic pattern responsible for the execution of the maximum speed forearm flexion movement is well documented (Angel, 1974, 1981a, 1981b; Boucher and Flieger, 1983; Flieger, 1983; Lagasse, 1975, 1979; Wachholder and Altenburger, 1926). Figure 2 gives a schematic representation of the electromyographic pattern to be expected for a given trial of the maximum speed forearm flexion movement. As can be seen on Figure 2, in addition to the three major expected integrated electromyographic bursts the m. triceps brachii integrated electromyographic burst is always preceded by a low intensity cocontraction period. A special technique, described below, was developed to quantify, from the integrated electromyographic recordings, 12 temporal and six quantitative integrated electromyographic pattern parameters, as well as two of the five kinematic parameters described above. Figure 3 depicts the 12 following temporal integrated electromyographic pattern parameters that will be quantified:

-Temporal integrated electromyographic pattern parameters

Biceps brachii first integrated electromyographic burst motor time (T1): time elapsed between the onset of the biceps brachii first integrated electromyographic burst and the onset of the maximum speed forearm flexion movement as represented by the first event marker.

Triceps brachii integrated electromyographic burst motor time (T2): time elapsed between the onset of the triceps brachii integrated electromyographic burst and the reaching of the 90 degree target as represented by the second event marker.

Triceps brachii cocontraction period motor time (T3): time elapsed between the onset of the triceps brachii cocontraction period and the onset of the maximum speed forearm flexion movement as represented by the first event marker.

Biceps brachii first integrated electromyographic burst duration (T4): time elapsed between the onset and end of the biceps brachii first integrated electromyographic burst.

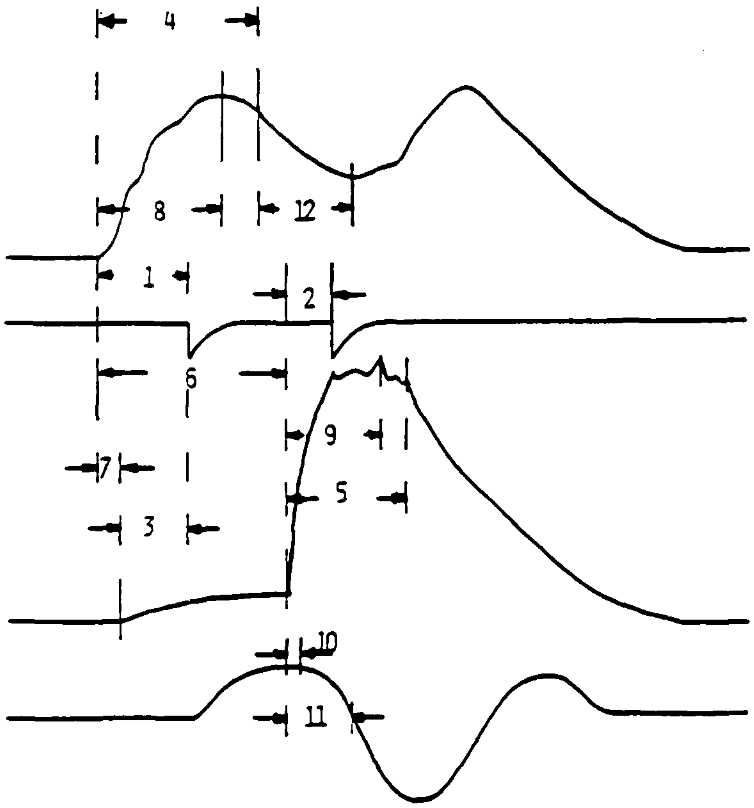

Figure 3. Schematic representation of the 12 temporal integrated electromyography pattern parameters (see text for parameter descriptions).

Triceps brachii integrated electromyographic burst duration (T5): time elapsed between the onset and end of the triceps brachii integrated electromyographic burst.

Biceps brachii to triceps brachii integrated electromyographic latency (T6): time elapsed between the onset of the biceps brachii first integrated electromyographic burst and the onset of the triceps brachii integrated electromyographic burst.

Biceps brachii to triceps brachii cocontraction period latency (T7): time elapsed between the onset of the biceps brachii first integrated electromyographic burst and the onset of the triceps brachii cocontraction period.

Biceps brachii first integrated electromyographic burst time to peak integrated electromyographic activity (T8): time elapsed between the onset of the biceps brachii first integrated electromyographic burst and its peak integrated electromyographic activity.

Triceps brachii integrated electromyographic burst time to peak integrated electromyographic activity (T9): time elapsed between the onset of the triceps brachii integrated electromyographic burst and its peak integrated electromyographic activity.

Triceps brachii integrated electromyographic burst to the point of maximum acceleration latency (T10): time elapsed between the onset of the triceps brachii integrated electromyographic burst and the point of maximum or peak positive acceleration.

Triceps brachii integrated electromyographic burst to the specific acceleration-deceleration point of inflexion latency (T11): time elapsed between the onset of the triceps brachii integrated electromyographic burst and the specific acceleration-deceleration point of inflexion.

Biceps brachii integrated electromyographic silent period (T12): time elapsed between the end of the biceps brachii first integrated electromyographic burst and the onset of the biceps brachii second integrated electromyographic burst.

Figure 4 presents the six quantitative integrated electromyographic pattern parameters defined below:

-Quantitative integrated electromyographic pattern parameters

Biceps brachii first integrated electromyographic burst peak activity (Q1): peak integrated electromyographic amplitude for the biceps brachii first integrated electromyographic burst.

Biceps brachii second integrated electromyographic burst peak activity (Q2): peak integrated electromyographic amplitude for the biceps brachii second integrated electromyographic burst.

Triceps brachii integrated electromyographic burst peak activity (Q3): peak integrated electromyographic amplitude for the triceps brachii integrated electromyographic burst.

Slope of the biceps brachii first integrated electromyographic burst (Q4): initial rate of increase of the biceps brachii first

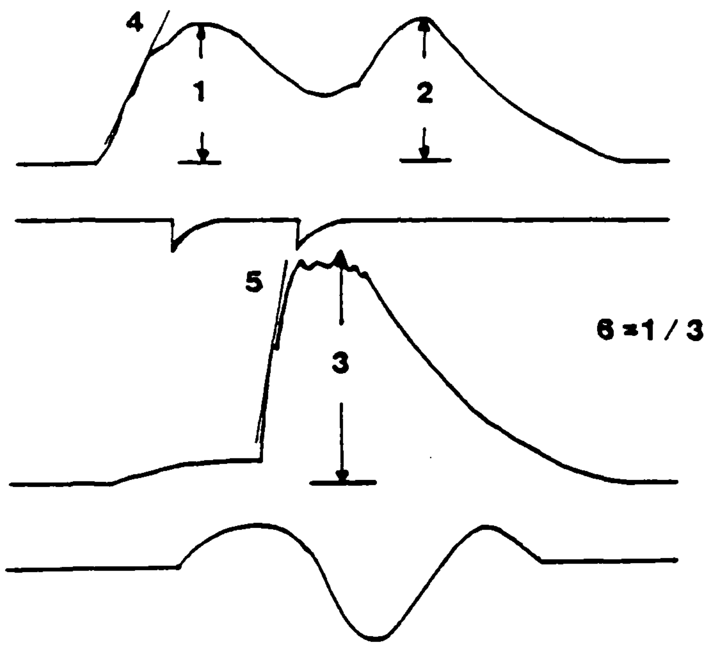

Figure 4. Schematic representation of the six quantitative integrated electromyography pattern parameters (see text for parameter descriptions).

integrated electromyographic burst integrated electromyographic activity.

Slope of the triceps brachii integrated electromyographic burst (Q5): initial rate of increase of the triceps brachii integrated electromyographic burst integrated electromyographic activity.

Integrated electromyographic ratio (Q6): ratio of the biceps brachii first integrated electromyographic burst peak activity to the triceps brachii integrated electromyographic burst peak activity.

The temporal electromyographic analysis was shown to yield meaningful information regarding the neuromuscular coordination control mechanisms responsible for the control of the muscle contractions involved in the maximum speed forearm flexion movement as well as other type of movements (Boucher, 1980; Lagasse, 1975, 1979). Quantitative parameters, such as integrated electromyographic ratio and peak integrated electromyographic activity, were found to have a great predictive value for maximum speed of human movement (Kilmer et al., 1982) and isometric tension output (Bigland and Lippold, 1954; Lippold, 1952). However, information regarding the predictive value of

such parameters for movement time and their information content regarding the neuromuscular coordination control mechanisms underlying the maximum speed forearm flexion movement still remains scarce.

Finally, the last type of information monitored was the tension output for the forearm flexion and extension. Isometric maximum voluntary contraction of the flexor and extensor muscle groups were executed and monitored by having the subjects pull against a Statham strain gauge. The tension output signal was displayed on the Beckman chart recorder along with the m. biceps brachii and the m. triceps brachii integrated electromyographic signals. Peak tension output of each isometric maximum voluntary contraction trial were taken to represent maximum isometric strength.

Measurement Techniques

This section presents the measurement techniques utilized in order to record all information and to quantify all the parameters mentioned above. Three subsections compose this section, and they are: measurement of the kinematic information, the integrated electromyographic information, and the isometric

maximum voluntary contraction information.

Kinematic information

As mentioned above, angular displacement, velocity and acceleration were monitored. The angular displacement signal was derived from a potentiometer mounted along the axis of rotation of the elbow joint (Figure 1). The angular displacement signal was in turn fed into a specially built analog signal differentiator (Lagasse and Jakus, 1973) and differentiated twice resulting into angular velocity and acceleration. Therefore, the output of the analog signal differentiator consisted of the three angular kinematic signals recorded on every testing day trial. The measurement of movement time and time of positive acceleration was done through a set of two microswitches and the analog signal differentiator. As described above, upon onset of the maximum speed forearm flexion movement a first microswitch was activated , triggering then the movement time millisecond timer. This timer was stopped by a second microswitch activated when the forearm reached the 90 degree target.

The time of positive acceleration was monitored by a second millisecond timer controlled by the analog signal differentiator. This last timer was activated upon onset of the maximum speed forearm flexion movement, as for the movement time millisecond

timer, and stopped by the analog signal differentiator. The time of positive acceleration millisecond timer was stopped as soon as the acceleration signal, derived from the analog signal differentiator, reached a zero value immediately before the forearm initiated the deceleration or negative acceleration phase. This point of zero acceleration is referred to as the specific acceleration-deceleration point of inflexion (Boucher, 1980; Boucher and Lagasse, 1980; Lagasse, 1975). Finally, from the time of positive acceleration the standardized acceleration time (i.e., time of positive acceleration expressed as a percent of movement time) was derived, and the maximum displacement and the time to maximum acceleration were derived from the integrated electromyographic pattern utilizing the integrated electromyography quantification software program described below.

Integrated electromyographic information

A standardized surface electromyographic technique was utilized to record the subject's electromyographic activity. Beckman bipolar surface electrodes (Ag-AgCl) were utilized to monitor simultaneously the analog electromyographic signals from the long head of the m. biceps brachii and the lateral head of the m. triceps brachii during each monitored maximum speed forearm flexion movement trial on all testing days. The active

electrodes remained in place over each target muscle's approximate motor point (Walthard and Tchicaloff, 1961) only after the skin to electrode resistance was reduced to 10 kohms or less using standard skin preparation procedures. The electrodes were secured to the skin with special adhesive collars. One active electrode was attached to the skin over the approximate motor point, whereas, the other was placed 4.25 cm (center-to-center) distally in a position parallel to the muscle fiber direction. In addition, a common reference electrode was attached to the skin overlying the right clavicle of each subject. The reference electrode was placed on a bony area following Boucher and James (1982) recommendations. The analog electromyographic signal was then amplified, integrated and recorded using Beckman couplers (type 9852), apmplifiers and chart recorder (type R). Figure 2 displays a typical maximum speed forearm flexion movement trial as recorded on the Beckman chart recorder.

Following all testing days a specially developed integrated electromyography quantification software program was utilized to compute the temporal and quantitative integrated electromyographic parameters as well as two of the five kinematic parameters. This integrated electromyography quantification software program, developed by the author based

upon Boucher and Lagasse (1979) algorithm, was developed on a NOVA-3 minicomputer (Data General Corporation) interfaced with a sonic-sensory screen and a Grafpen (model GP3, Science Accessories Corporation). The quantification of the temporal and quantitative integrated electromyographic parameters is based upon the digitization of 15 specific points prelocated on an integrated electromyographic record of a maximum speed forearm flexion movement trial. Figure 5 presents a schematic representation of the 15 specific digitizing points along a typical record of a maximum speed forearm flexion movement trial, and table 1 presents a description of these 15 points. From those 15 specific points and the proper electromyographic amplifier sensitivity and recorder paper speed settings requested by the integrated electromyography quantification software program, the integrated electromyographic parameters were quantified and stored on magnetic discs for later analysis.

Tension output information

During isometric maximum voluntary contraction subjects were in the same position as for the maximum speed forearm flexion movement; i.e., chest braced against the padded movement apparatus, the upper arm parallel to, and supported by, the apparatus top at a 90 degree angle to the shoulder in the sagittal plane. The forearm was positioned at angles of 75

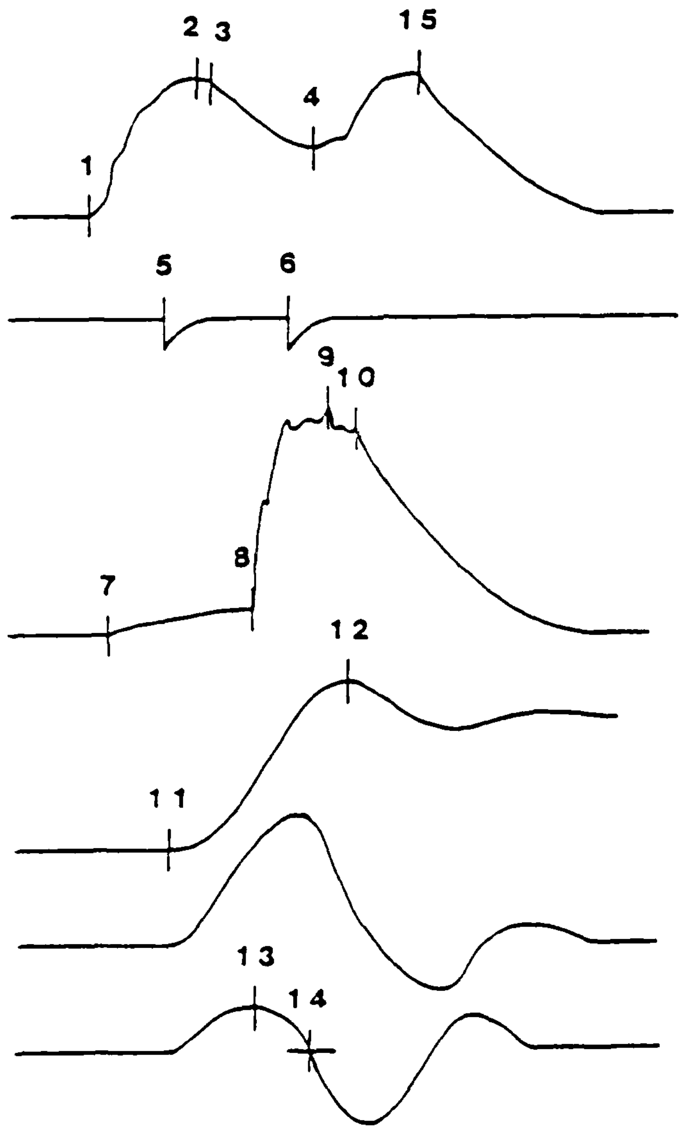

Figure 5. Schematic representation of the 15 specific digitizing points along the integrated electromyography pattern.

TABLE 1

Description of the 15 specific digitizing points. IEMG: integrated electromyographic.

POINTS	DESCRIPTIONS
1.	Onset of the biceps brachii first IEMG burst.
2.	Peak activity of the biceps brachii first IEMG burst.
3.	End of the biceps brachii first IEMG burst.
4.	Onset of the biceps brachii second IEMG burst.
5.	Movement onset event marker.
6.	90 degree target event marker.
7.	Onset of the triceps brachii cocontraction period.
8.	Onset of the triceps brachii IEMG burst.
9.	Peak activity of the triceps brachii IEMG burst.
10.	End of the triceps brachii IEMG burst.
11.	Onset of movement displacement curve.
12.	Maximum displacement.
13.	Maximum acceleration.
14.	Specific acceleration-deceleration point of inflexion.
15.	Peak activity of the biceps brachii second IEMG burst.

degrees for flexion and 90 degrees for extension. In accordance with Basmajian and Latif (1957), the elbow angles are given as the complement of the angle between the forearm and the upper arm. A wrist cuff directly connected to a Statham strain gauge through a series of nuts and bolts (Figure 6) was utilized to monitor tension output. In turn, the tension output signal was recorded on the Beckman chart recorder. The angle of the pull for all isometric maximum voluntary contraction trials was at 90 degrees to the strain gauge with the hand and forearm in a semiprone position. Forearm position is known to affect the expression of the forearm flexion and extension strength; however, the use of a wrist cuff effectively eliminates such effects (Provins and Salter, 1955). Alterations in forearm position from the midline during maximal efforts would thus not affect the expression of maximum strength.

Testing Schedule

All the subjects had to report to the Motor Integration Laboratory for three pre-test days and two post-test days. The pre-test days were at most 48 hours apart, whereas, the last pre-test day and the two post-test days were interspersed with two weeks of experimental treatment.

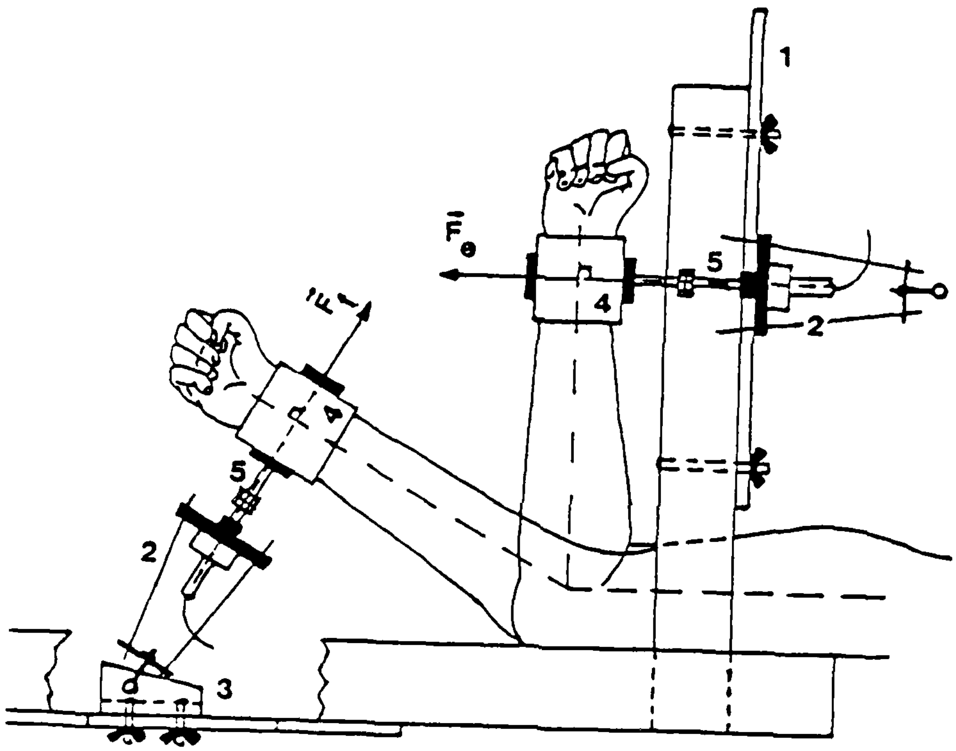

Figure 6. Isometric maximum voluntary contraction tension output measurement apparatus. F_f: flexor resultant force vector; F_e: extensor resultant force vector; (1) adjustable strain gauge support for extension; (2) strain gauge; (3) adjustable strain gauge support for flexion; (4) wrist cuff; (5) nuts and bolts link between wrist cuff and strain gauge.

Pre-test days

All subjects, regardless of the experimental group in which they were assigned participated in three pre-test days. Those pre-test days were designed to allow stabilization of the maximum speed forearm flexion movement integrated electromyographic pattern and performance. In other words, those pre-test days were realized in order to allow motor learning of the maximum speed forearm flexion movement to occur. Stabilization of performance can traditionally be observed as a reduction followed by a leveling off of the performance criterion, movement time.

On each pre-test day 15 successful trials of the maximum speed forearm flexion movement were administered to the subjects in order to induce performance stabilization. The success criterion for a given trial was defined by the level of accuracy or the degree of overshoot of the 90 degree target. For obvious reasons, out of the daily 15 trials only the last five trials were recorded for quantification and analysis purposes. Following the maximum speed forearm flexion movement trials forearm flexion and extension maximal isometric strength were monitored.

Four isometric maximum voluntary contractions were secured for the right forearm flexion and extension strength. Each trial

was separated by a one minute rest interval, whereas, the interseries rest interval was of seven to ten minutes. The order of flexion and extension isometric maximum voluntary contraction testing was balanced over subjects. According to previous results obtained in this laboratory (Kroll, Kilmer, Bultman and Boucher, 1983) no differences in mean strength due to the testing order should occur. The four isometric maximum voluntary contractions were executed under two conditions. Two trials were standard isometric maximum voluntary contraction measures where the subjects were instructed to exert a maximal contraction for five seconds (Kroll, 1973). The other two trials were fast isometric maximum voluntary contraction measures where the subjects were instructed to reach maximal tension output as quickly as possible and maintain maximum tension until commanded to stop. Peak tension output of each trial was taken as maximum strength.

Post-test days

Both post-test days were very similar to the pre-test days. The only difference was that five maximum speed forearm flexion movement trials were administered. Only five trials were selected so that the testing schedule did not disturb the experimental treatment in progress. Lagasse (1975) demonstrated that at least 7 to 15 trials are necessary to induce performance

modification in the maximum speed forearm flexion movement. Therefore, administering five trials of the maximum speed forearm flexion movement halfway through the experimental treatment period (at the first post-test) should not influence the effects of the experimental treatment in progress. The purpose of testing performance halfway through the experimental treatment was to inspect the possible modifications occurring in the maximum speed forearm flexion movement integrated electromyographic pattern due to the experimental treatment and readjust, when necessary, the functional electrical stimulation pattern of the subjects in the concerned groups.

Experimental treatment sessions

Following the pre-test days the subjects were randomly allocated into six different experimental groups: two control groups (a passive and a traditional practice control group) and four functional electrical stimulation groups (high frequency progression, high frequency retrogression, low frequency progression and low frequency retrogression functional electrical stimulation groups). All subjects for all groups participated in two two-weeks experimental treatment periods. After each two-week period, post-test measurements were realized as described above. The experimental treatment administered to a given subject depended upon the group in which he or she had been

assigned.

Control groups. Two control groups were utilized in the present investigation; a passive control group and a traditional practice control group. The passive control group was subjected to three pre-test days followed by two weeks in which no experimental treatment was administered, and a post-test day. Then, another two-week period, again devoid of experimental treatment, followed by a last post-test day was administered.

The traditional practice group took part in three pre-test days followed by four weeks of traditional practice of the maximum speed forearm flexion movement as experimental treatment. As for the passive control group, post-test days were administered after every two-week period for a total of two post-test days. The traditional practice experimental treatment consisted of executing successful repetitions of the maximum speed forearm flexion movement. A two-week traditional practice period was constituted of three practice sessions a week, for a total of six practice sessions per two-week period. On a practice session a subject was asked to execute 60 successful repetitions of the maximum speed forearm flexion movement at a rate of one repetition every 30 seconds. In an attempt to standardize the practice sessions, tape recorded intructions and repetition commands were utilized by the subjects. A 5-minute

rest interval was given halfway through a practice session if a subject felt a need for it.

<u>Functional electrical stimulation groups</u>. This study proposed to compare the effects of four different functional electrical stimulation treatments. The four functional electrical stimulation groups consisted of two high frequency functional electrical stimulation groups and two low frequency functional electrical stimulation groups. In both high and low frequency groups, the two groups were a progression group and a retrogression group. As for the control groups, each subject of the functional electrical stimulation groups received three pre-test days followed by two two-weeks experimental treatment periods and each, in turn, followed by a post-test day. For all functional electrical stimulation groups, the subjects were administered six treatment sessions per two-week period (three per week). Each treatment session consisted of half an hour of actual experimental treatment, functional electrical stimulation in this case, and of the following ten procedure points:

1. Secure the stimulation electrodes: Before functional electrical stimulation treatment, carbon rubber (Medtronic Inc.) stimulation electrodes were secured on the skin over the m. biceps brachii and the m. triceps brachii. The

stimulation electrodes were covered with a special electrolyte gel, maintained over the skin with specially designed velcro band, then connected to the stimulation isolating unit (Grass, model SIU5A) which was in turn connected to the dual channel Grass stimulator (model S88). Following the Rancho Los Amigos functional electrical stimulation guide recommendations (Benton, Baker, Bowman and Waters, 1980), the cathode or active electrode was of smaller surface area (15.75 cm^2) and located over the approximate motor point in order to make the electrode more active and increase the density of current to the underlying muscle. The anode or indifferent electrode was of greater surface area (50 cm^2) and secured distally to the cathode over the same target muscle. Finally, in order to insure subject safety during functional electrical stimulation treatment the electrodes were connected to the stimulator through isolating units and proper grounding of the instrument was insured.

2. Establishe rheobase: Rheobase, current applied for an infinitely long period of time (traditionally 300 milliseconds) necessary to elicit a minimal visible muscle contraction, was determined for each muscle before every treatment session. In order to determine rheobase, stimulation pulse duration was adjusted at 300 milliseconds

and the stimulation current increased slowly until a visible contraction was obtained. The current thus found was taken as the muscle rheobase.

3. Set the stimulation voltage to the pulse duration determination voltage (see equation in Appendix C).

4. Determine the single pulse duration: The single pulse duration, defined as the minimal single pulse duration that will elicit a visible muscle contraction for a pulse duration determination voltage stimulation intensity, was established for each muscle before each treatment session. The single pulse duration was ascertained by setting the stimulator intensity at the pulse duration determination voltage and slowly increasing the single pulse duration until a visible muscle contraction was obtained.

5. Set the stimulus intensity (see equation in Appendix C).

6. Set the biceps brachii to triceps brachii functional electrical stimulation pattern latency (see equation in Appendix C).

7. Set the m. biceps brachii and m. triceps brachii functional electrical stimulation train duration: The specific muscle train duration was defined as the total duration of the muscle stimulation within one functional electrical stimulation pattern. The functional electrical stimulation train duration was derived from the integrated electromyographic maximum speed forearm flexion movement pattern. The m. biceps brachii functional electrical stimulation train duration was set equal to the integrated electromyographic pattern biceps brachii first burst duration and, similarly, the m. triceps brachii functional electrical stimulation train duration was set equal to the integrated electromyographic pattern triceps brachii burst duration.

8. Set the pulse frequency: As suggested above, the effects of high and low frequency functional electrical stimulation treatment were studied. The low frequency was set at 50 hertz, whereas, the high frequency was set at 1000 hertz. Those two frequency settings were selected in order to have one frequency setting within the normal physiologic range of motor unit firing (50 hertz), and another outside of that range (1000 hertz).

9. Functional electrical stimulation treatment: For each subject of eacn functional electrical stimulation group a treatment period was of 30 minutes, with one functional electrical stimulation pattern (Figure 7), also referred to as sensory imparted learning unit (Lagasse et al., 1982), administered every 10 seconds for a total of 180 functional electrical stimulation patterns or sensory imparted units per treatment period.

10. Remove and clean the stimulation electrodes.

Functional electrical stimulation model. All functional electrical stimulation pattern parameters utilized during the treatment period for each functional electrical stimulation group were derived from the general functional electrical stimulation model presented in Appendix C. The functional electrical stimulation model was developed in order to individualize the functional electrical stimulation pattern parameters.

Lagasse et al. (1979) were probably the first to try to standardize stimulation intensity by monitoring rheobase and defining the stimulation intensity by adding a constant voltage to the rheobase value. However, the functional electrical stimulation technique utilized in their study, as in many other functional electrical stimulation research endeavors (Boucher,

1980; Carnstam and Larsson, 1974; Fleury and Lagasse, 1979; Kots, 1971; Kralj and Vodovnik, 1977; Massey, Nelson, Sharkey and Comden, 1965), did not take interindividual differences into consideration. All subjects that were administered functional electrical stimulation were treated with the same functional electrical stimulation pattern regardless of their own individual motor pattern responsable for the motor task at hand. Therefore, in an effort to individualize the functional electrical stimulation treatment the functional electrical stimulation model (see Appendix C) was developed.

As for the integrated electromyographic pattern, a functional electrical stimulation pattern was composed of temporal and quantitative parameters. The m. biceps brachii and m. triceps brachii train duration and the biceps brachii to triceps brachii stimulation latency represent the temporal parameters. The stimulation intensity and the single pulse duration and frequency represent the quantitative paramenters. Traditionally, most of the quantitative parameters were the object of many research endeavors in which those parameters were taken as constant, thus, without taking subjects interindividual differences into consideration (Dimitrijevic, Gracanin, Prevec and Trontelj, 1968; Merletti, Zelaschi, Latella, Galli, Angeli and Sessa, 1975; Vodovnik and Rebersek, 1973). The temporal parameters were mostly ignored. Stimulations were applied to

target muscles, and more often to a single muscle, regardless of the temporal sequence in which the muscles or muscle are/is involved in the movement under investigation (Massey et al., 1965; Moreno-Aranda and Siereg, 1981a, 1981b, 1981c; Nowakowska, 1971). In the present study the lack of control over the functional electrical stimulation pattern parameters was overcome by utilizing the functional electrical stimulation model (see Appendix C).

Prior to functional electrical stimulation treatment, the functional electrical stimulation pattern temporal parameters were derived from the subject's own maximum speed forearm flexion movement integrated electromyographic pattern. As mentioned above, the train durations were derived from the respective muscles' integrated electromyographic burst duration. The stimulation biceps brachii to triceps brachii latency, as well as the quantitative functional electrical stimulation parameters were adjusted following the functional electrical stimulation model and according to the target functional electrical stimulation group. Four different functional electrical stimulation treatments, therefore four different functional electrical stimulation groups, were involved in this investigation. The high frequency progression group, high frequency retrogression group, low frequency progression group, and the low frequency retrogression group, represent the four

functional electrical stimulation groups involved in this study. The high and low frequency groups refer to the functional electrical stimulation pattern pulse frequency, and it was set at 50 hertz for the low frequency groups and at 1000 hertz for high frequency groups. This large discrepancy in pulse frequency was utilized in order to assess the effects of pulse frequency upon the efficiency of the functional electrical stimulation treatment. The 50 hertz and 1000 hertz pulse frequencies were selected because the low pulse frequency is within the physiologic range of motor unit firing, whereas, the high frequency is considered above normal physiologic range of motor unit firing. Therefore, the indispensibility of keeping the stimulation pulse frequency within the motor unit firing frequency range was assessed.

The progression and retrogression groups refer to the direction in which the functional electrical stimulation pattern and performance were manipulated. The progression groups were stimulated with a functional electrical stimulation pattern modelled in such a way that it would be responsible for a faster movement. The retrogression groups were stimulated with a functional electrical stimulation pattern modelled to produce a slower movement. In both progression and retrogression groups, the biceps brachii to triceps brachii stimulation latency and the functional electrical stimulation pattern quantitative parameters

were modified by 10% of their original values found in the maximum speed forearm flexion movement integrated electromyographic pattern. The biceps brachii to triceps brachii stimulation latency was increased by 10% for the progression group and was decreased by 10% for the retrogression group. Since it was demonstrated by Lagasse (1975) that the biceps brachii to triceps brachii electromyographic latency is related to movement time, it was hypothesized that manipulating that parameter would enable performance modification. According to Lagasse (1975), the longer the biceps brachii to triceps brachii electromyographic latency the shorter the movement time up to a certain point. Therefore, the biceps brachii to triceps brachii stimulation latency was made longer than the biceps brachii to triceps brachii integrated electromyographic latency for the progression groups, and shorter than the biceps brachii to triceps brachii integrated electromyographic latency for the retrogression groups. Finally, Figure 7 presents a schematic representation of a typical functional electrical stimulation pattern and Figure 8 schematically depicts the testing and experimental treatment schedule utilized in this study.

Statistical Analysis

Following data collection, reduction and quantification,

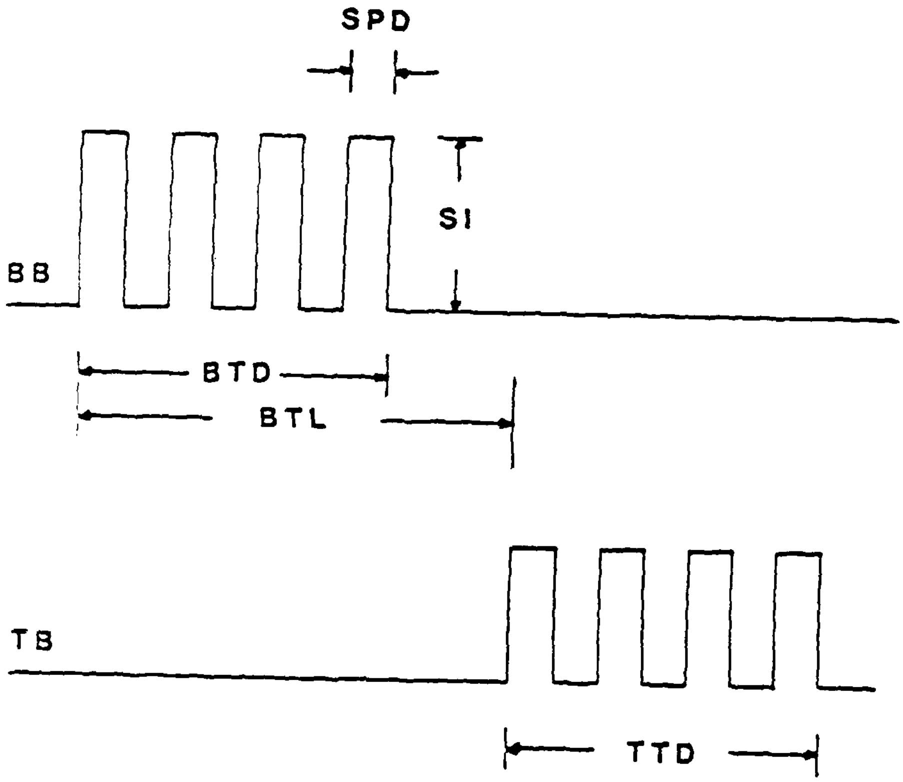

Figure 7. Schematique representation of a typical functional electrical stimulation pattern. BB: biceps brachii; BTD: biceps brachii train duration; BTL: biceps brachii to triceps brachii functional electrical stimulation pattern latency; SI: stimulation intensity; SPD: single pulse duration; TB: triceps brachii; TTD: triceps brachii train duration.

	PRE-TEST DAYS		TREAT PERIOD 1		TREAT PERIOD 2	
<u>CONTROL GROUPS</u>						
PASSIVE			no treatment		no treatment	
		L		P		P
TRADITIONAL	3 days	A	6 sessions	O	6 sessions	O
PRACTICE		S	60 reps/ses	S	60 reps/ses	S
		T		T		T
<u>HIGH FRE FES GROUPS</u>		P				
	15 trials	R		T		T
PROGRESSION	per	E		E		E
	day		6 sessions	S	6 sessions	S
RETROGRESSION		T		T		T
		E				
		S	30 min/ses		30 min/ses	
<u>LOW FRE FES GROUPS</u>	4 flexor	T		D		D
	&			A		A
PROGRESSION	4 extensor	D	1 FES patt	Y	1 FES patt	Y
		A	every		every	
RETROGRESSION	IMVC	Y	10 sec	1	10 sec	2

Figure 8. Schematic representation of the testing and treatment schedule (functional electrical stimulation: FES; treatment: TREAT; session: ses; pattern: patt; repetitions: reps; mimute: min; second: sec).

descriptive statistics as well as intraclass reliability were assessed first. The stability, across the three pre-test days, of the parameters monitored was assessed using an analysis of variance model with repeated measures. Then, the consistency of the parameters was assessed by further comparing the second and last pre-test days using an analysis of variance intraclass correlation model. For all reliable parameters the experimental hypotheses were ascertained utilizing a split-split-plot analysis of variance design (Steel and Torie, 1980) in comparing the last pre-test and two post-test days. This statistical design can also be referred to as a three way factorial design with repeated measures on the two last factors (Winer, 1971). For statistically significant results a Duncan (1955) multiple range test was carried out for the days main effects. Table 2 presents the analysis of variance table, including the sources of variance, degrees of freedom, the estimations of mean squares and proper F ratios, for the statistical design presented above. Finally, the predictability of the performance criterion, movement time, by the experimental parameters was ascertained using a forward and backward stepwise linear multiple regression model.

TABLE 2

Split-split-plot design analysis of variance table

Sources of variations	Degrees of freedom	E(MS)	F
Treatments (G)	35		
G	5	$\sigma^2 w + 15\ \sigma^2 s{:}g + 90\ \sigma^2 g$	MS_{G}/MS_{E1}
E1 (S:G)	30	$\sigma^2 w + 15\ \sigma^2 s{:}g$	
Days (D)	72		
D	2	$\sigma^2 w + 5\ \sigma^2 ds{:}g + 180\ \sigma^2 d$	MS_{D}/MS_{E2}
DG	10	$\sigma^2 w + 5\ \sigma^2 ds{:}g + 30\ \sigma^2 dg$	MS_{DG}/MS_{E2}
E2 (DS:G)	60	$\sigma^2 w + 5\ \sigma^2 ds{:}g$	
Trials (T)	432		
T	4	$\sigma^2 w + 3\ \sigma^2 ts{:}g + 108\ \sigma^2 t$	MS_{T}/MS_{E3}
TG	20	$\sigma^2 w + 3\ \sigma^2 ts{:}g + 18\ \sigma^2 tg$	MS_{TG}/MS_{E3}
E3 (TS:G)	120	$\sigma^2 w + 3\ \sigma^2 ts{:}g$	
TD	8	$\sigma^2 w + \sigma^2 tds{:}g + 36\ \sigma^2 td$	MS_{TD}/MS_{E4}
TDG	40	$\sigma^2 w + \sigma^2 tds{:}g + 6\ \sigma^2 tdg$	MS_{TDG}/MS_{E4}
E4 (TDS:G)	240	$\sigma^2 w + \sigma^2 tds{:}g$	
Total	539		

RESULTS

Introduction

The data to be analysed consisted of kinematic, integrated electromyographic pattern, and tension output parameters. The five kinematic parameters are the following: (K1) movement time, (K2) time of positive acceleration, (K3) percent acceleration time, (K4) maximum displacement, and (K5) time to maximum acceleration. The integrated electromyographic pattern parameters were divided into 12 temporal parameters (T1 to T12) and six quantitative parameters (Q1 to Q6). Finally, the tension output parameters consisted of the flexors and extensors normal and fast maximal isometric tension output.

All parameters were collected on 36 subjects randomly

allocated into two control groups (passive and traditional practice control groups) and four functional electrical stimulation groups (high frequency progression and retrogression, and low frequency progression and retrogression functional electrical stimulation groups) on three pre-test and two post-test days. The pre-test days, administered before the experimental treatment periods, were at most 48 hours apart, whereas, the last pre-test and two post-test days were separated with two two-week periods of experimental treatment. These five testing days were designed to assess the experimental parameters during the execution of the experimental movement: a class B maximum speed forearm flexion movement executed through the sagittal plane with the forearm in a semi-prone position.

All parameters were analysed first to test for the effects of performance stabilisation and the stability and consistency of the parameters collected. Secondly, the experimental treatment effects across days and between treatments or groups were assessed. Lastly, the predictability of the performance criterion (movement time) was analysed. For analysis purposes the five testing days were divided into two independent periods: (1) the performance stabilization period composed of the three pre-test days, and (2) the experimental treatment period including the last pre-test and the two post-test days.

For presentation purposes, the results are divided into four sections: (1) sample size adequacy analysis, which presents the results of the power analysis executed on the data collected; (2) reliability, which presents performance stabilisation results along with the stability and consistency analysis of all parameters monitored; (3) treatment effects; this section deals with the results of the analysis of the experimental treatment effects across days and trials, and over treatments or groups; and (4) performance predictability which presents the effects of performance stabilisation upon the multiple regression equation predicting the performance criterion (movement time).

Sample Size Adequacy Analysis

The adequacy of the sample size was realized by calculating the power for the performance criterion (movement time) analysis. The power was assessed by Tang's method (1938). This method consists of calculating a ϕ parameter which is roughly the treatment effect divided by the standard error of measurement. This parameter is defined as follows:

$$\phi = \frac{\sqrt{\sum_{j=1}^{k} \beta_j^2 / k}}{\sigma_\varepsilon / \sqrt{n}}$$

where: β_j = treatment effect for the jth treatment.
k = number of treatments.
n = number of elements.
σ_ε = error variance.

As suggested by Kirk (1968), the different components of this parameter can be assessed as follows:

$$\sigma_\varepsilon = \sqrt{MS_{error}}$$

$$\sum_{j=1}^{k} \beta_j^2 = \frac{k - 1}{n} \cdot (MS_{treat} - MS_{error})$$

where: MStreat = treatment effect mean squares.
MSerror = error mean squares.
k = number of treatments or groups.
n = number of elements.

Finally, by establishing the proper degrees of freedom and confidence level, the power can be evaluated.

As for the sample size estimation analysis, the sample size adequacy or power analysis will be performed for the treatment

effects over time (day effect) as well as for the treatment condition effects (group effect). These two separate analyses should yield the power for the two questions addressed by this study: (1) what are the effects of the functional electrical stimulation treatments upon the neuromuscular coordination control mechanisms (day effect); and (2) what are the effects of different functional electrical stimulation treatment conditions (group effect).

Treatment effects sample size adequacy

This sample size adequacy analysis was performed in order to assess the power of the tests on the functional electrical stimulation treatment effects over time. After using Tang's method (1938) as presented above for a confidence level of 0.05, the post experimental power was found to be of 98% for the treatment effects over time (Appendix D). Thus, the sample size (n=6 subject per group) utilized in this study appeared to be more than adequate. Furthermore, this result shows the adequacy with which this treatment effect can be determined as well as the effectiveness of the experimental design utilized

Treatment condition effects sample size adequacy

The treatment condition comparison sample size adequacy

analysis yielded a power of 65% (Appendix D). Based upon the sample size estimation a power of 50% was assumed in order to get a sample size of 6 subjects per group for the treatment condition effects. The post experimental power is then a little higher than the one established pre experimentaly for this test. However, this relatively low post experimental power represents a limitation which should be taken into consideration.

Reliability of Experimental Parameters

The data analyzed herein consist of the five kinematic (K1 to K5), 12 temporal integrated electromyographic (T1 to T12), six quantitative integrated electromyographic (Q1 to Q6), and four tension output parameters presented above. These parameters were collected on three pre-test and two post-test days. On each test day, kinematic and integrated electromyographic data were collected on five trials of the maximum speed forearm flexion movement, whereas, tension output parameters were monitored during eight separate isometric maximal voluntary contractions (4 flexions and 4 extensions).

The results presented below were obtained from the performance stabilization period. Therefore, this section serves

the double purpose of presenting the reliability of the parameters and the degree of stabilisation that occurred across the three pre-test days. Inherent in the design of this experiment is the paradox that the performance stabilisation effect, occurring with practice, may simultaneously weaken the reliability of a given parameter. Furthermore, the inconsistency of the parameters, as indicated by intraclass correlation coefficients, would also confound any performance stabilisation effects. The reliability analysis is of special significance to the present study since most of the parameters analyzed were assessed by a novel integrated electromyography quantification technique.

For the four functional electrical stimulation groups, several parameters were monitored on every stimulation session. As presented in the second chapter, the rheobase, single pulse duration and stimulus intensity were set and recorded at the beginning of every stimulation session for both the biceps brachii and triceps brachii muscles. Therefore, the results of the reliability analysis performed on these parameters will also be presented below.

Finally, this section is divided into three parts in order to present all aspects of data reliability. First, descriptive statistics, means and standard deviations, are presented to

illustrate the variability of the parameters between groups and across days. Second, the stability of the parameters, assessed through a split-split-plot analysis of variance model, is displayed, and third, the consistancy evaluated by an intraclass reliability model, will be presented.

Descriptive statistics

Kinematic parameters. Tables 3 to 7 present the means(M) and standard deviations (SD) for the day and group main effects, and for the day-group interaction, for the five kinematic parameters. As shown on table 3, the stabilization period was responsible for an 8 ms decrease in movement time from day 1 to day 3 (from 147 ms to 139 ms). The movement time standard deviations also decreased from day 1 to day 3, ranging from 31 ms to 22 ms, suggesting that practice had for effect not only of increasing the speed of movement but also of rendering the subjects more homogeneous. Furthermore, all groups except for the control group (group 1) displayed a decrease in mean movement time with practice. Such decrease in movement time corroborates previous finding reported by Boucher (1980), Flieger (1983) and Lagasse (1975, 1979) among others (Finley et al, 1967; Hobart et al, 1975; Normand et al, 1982; Wolcott, 1977). The time of positive acceleration means and standard deviations (table 4) followed the same trend as for movement time (increased over

TABLE 3

Means (M) and standard deviations (SD) for the movement time (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	131	132	131	131
	SD	12	13	17	14
2	M	150	148	144	147
	SD	19	21	18	19
3	M	132	132	128	131
	SD	17	12	15	15
4	M	143	140	136	140
	SD	45	39	31	38
5	M	163	156	149	156
	SD	27	18	24	24
6	M	162	154	149	155
	SD	38	17	17	26
DAY MEANS	M	147	144	139	GM= 143
	SD	31	24	22	26

TABLE 4

Means (M) and standard deviations (SD) for the time of positive acceleration (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	101	101	105	102
	SD	15	10	15	13
2	M	129	120	117	122
	SD	26	18	20	22
3	M	109	103	108	107
	SD	15	13	12	14
4	M	121	114	112	116
	SD	34	31	19	29
5	M	133	127	125	128
	SD	16	21	10	16
6	M	126	130	118	125
	SD	18	20	20	20
DAY MEANS	M	120	116	114	GM= 117
	SD	24	23	18	22

TABLE 5

Means (M) and standard deviations (SD) for the percent acceleration time (%) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	77.5	77.3	81.0	78.6
	SD	12.3	10.3	12.1	11.6
2	M	85.9	81.3	81.8	83.0
	SD	12.8	7.5	13.1	11.5
3	M	83.6	78.5	84.8	82.3
	SD	11.3	10.2	9.9	10.7
4	M	85.8	82.7	84.5	84.3
	SD	11.5	10.8	13.5	11.9
5	M	82.4	81.7	85.2	83.1
	SD	10.4	11.2	10.5	10.7
6	M	80.5	84.5	79.9	81.6
	SD	13.8	9.6	15.5	13.2
DAY MEANS	M	82.6	81.0	82.9	GM= 82.2
	SD	12.3	10.2	12.6	11.7

TABLE 6

Means (M) and standard deviations (SD) for the maximum displacement (degrees) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	113	114	117	115
	SD	9	9	10	9
2	M	120	118	116	118
	SD	14	17	13	14
3	M	106	108	114	110
	SD	7	9	10	10
4	M	113	108	108	110
	SD	17	10	10	13
5	M	107	108	111	109
	SD	8	8	6	8
6	M	111	112	116	113
	SD	8	9	8	9
DAY MEANS	M	112	111	114	GM= 112
	SD	12	11	10	11

TABLE 7

Means (M) and standard deviations (SD) for the time to maximum acceleration (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	94	97	88	93
	SD	20	21	27	23
2	M	109	109	88	102
	SD	21	21	23	24
3	M	78	82	76	79
	SD	23	14	22	20
4	M	80	92	80	84
	SD	21	24	21	22
5	M	82	91	101	91
	SD	23	20	27	25
6	M	91	102	97	97
	SD	34	37	23	32
DAY MEANS	M	89	96	88	GM= 91
	SD	26	25	25	26

days). Therefore, the percent acceleration time, which is by definition the time of positive acceleration expressed as a percent of movement time, was shown to be stable from day 1 to day 3 over all groups (ranging from 82.6% to 82.9%) as well as within groups (table 5). These results are not in accord with findings previously reported by Lagasse (1972) and Wolcott (1977), but support results presented by Flieger (1982) and Teves (1981). However, both Lagasse and Wolcott's data were collected on male subjects only, whereas, Flieger and Teves design included female subjects.

Table 6 presents the maximum displacement means and standard deviations. The day means over all groups were practically unchanged with practice. The maximum displacement ranged from 112 degrees on day 1 to 114 degrees on day 3. Similarly, the maximum displacement standard deviations remained constant (12, 11 and 10 degrees). The maximum displacement parameter is a measurement of the overshoot of the 90 degrees target which reflects the movement accuracy. Thus, performance stabilization through practice would seem to affect speed of movement without affecting movement accuracy. Traditionally, studies dealing with movement accuracy were interested in the effect of the target size (Fitts, 1954) without considering practice effects. Therefore, the present results were not compaired with previous studies.

The time to maximum acceleration descriptive statistics are presented in table 7. The mean time to maximum acceleration increased by 7 ms from day 1 to day 2 and decreased by 3 ms from day 2 to day 3. This peculiar trend suggests a high variability of this parameter which is corroborated by the high standard deviations (grand standard deviation of 26 ms). As for the previous parameter, the time to maximum acceleration represents a novel parameter and, therefore, no corroborating study could be found.

Temporal integrated electromyographic pattern parameters. Descriptive statistics for the temporal integrated electromyographic pattern parameters are presented in tables 8 to 19 inclusive. Tables 8, 9 and 10 present the data for the three motor time parameters: the biceps brachii first integrated electromyographic burst, triceps brachii integrated electromyographic burst, and the triceps brachii cocontraction period motor times respectively. The biceps brachii first integrated electromyographic burst motor time day means were shown to decrease during the stabilization period (from 68 ms to 64 ms) while the standard deviations remained relatively constant. The group means for this parameter were shown to vary greatly, varying from 56 ms for group 4 to 74 ms for group 5.

TABLE 8

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst motor time (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	65	60	58	61
	SD	12	10	10	11
2	M	71	74	70	72
	SD	12	9	15	12
3	M	70	64	60	65
	SD	10	14	12	13
4	M	54	58	56	56
	SD	15	15	15	15
5	M	78	71	72	74
	SD	10	8	14	11
6	M	73	72	70	72
	SD	11	20	23	19
DAY MEANS	M	68	66	64	GM= 66
	SD	14	14	17	15

TABLE 9

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst motor time (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	27	36	26	30
	SD	15	15	26	20
2	M	31	31	46	36
	SD	31	29	16	27
3	M	35	33	31	33
	SD	24	24	20	22
4	M	40	33	33	35
	SD	30	17	12	21
5	M	41	39	35	38
	SD	26	25	19	24
6	M	47	50	43	47
	SD	21	20	31	24
DAY MEANS	M	37	37	36	GM= 36
	SD	26	23	22	24

TABLE 10

Means (M) and standard deviations (SD) for the triceps brachii cocontraction period motor time (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	40	42	37	40
	SD	16	15	14	15
2	M	42	42	48	44
	SD	18	25	25	23
3	M	59	46	37	48
	SD	25	18	20	23
4	M	61	47	46	52
	SD	44	27	23	33
5	M	55	48	55	53
	SD	32	18	21	24
6	M	75	69	60	68
	SD	48	43	46	46
DAY MEANS	M	55	49	47	GM= 51
	SD	35	27	28	30

TABLE 11

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst duration (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	150	132	133	138
	SD	33	31	29	32
2	M	143	152	152	149
	SD	18	28	27	25
3	M	148	141	135	141
	SD	36	37	24	33
4	M	162	145	119	142
	SD	53	52	23	48
5	M	144	142	130	139
	SD	32	38	22	32
6	M	133	132	141	135
	SD	28	29	34	30
DAY MEANS	M	147	141	135	GM= 141
	SD	36	37	28	34

TABLE 12

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst duration (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	104	105	102	104
	SD	45	37	45	42
2	M	115	103	112	110
	SD	34	45	29	37
3	M	117	113	114	114
	SD	34	49	48	44
4	M	127	99	104	110
	SD	58	46	51	53
5	M	91	98	95	95
	SD	31	33	36	33
6	M	121	115	118	118
	SD	64	46	61	57
DAY MEANS	M	113	106	108	GM= 109
	SD	47	43	46	45

TABLE 13

Means (M) and standard deviations (SD) for the biceps brachii to triceps brachii integrated electromyographic latency (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	157	155	155	156
	SD	17	23	23	21
2	M	177	182	162	174
	SD	29	19	22	25
3	M	161	152	153	155
	SD	33	14	17	23
4	M	154	159	142	152
	SD	62	43	32	47
5	M	188	180	168	179
	SD	22	26	23	25
6	M	159	164	162	162
	SD	31	40	46	39
DAY MEANS	M	166	165	157	GM= 163
	SD	37	32	29	33

TABLE 14

Means (M) and standard deviations (SD) for the biceps brachii to triceps brachii cocontraction period ,latency (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	44	26	34	34
	SD	26	17	22	23
2	M	39	41	27	35
	SD	29	25	17	25
3	M	39	33	37	36
	SD	22	22	20	21
4	M	10	28	26	21
	SD	33	21	13	25
5	M	40	36	37	38
	SD	18	18	12	16
6	M	27	22	27	26
	SD	14	20	26	21
DAY MEANS	M	33	31	31	GM= 32
	SD	27	22	19	23

TABLE 15

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst time to peak integrated electromyographic activity (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	118	103	100	107
	SD	28	38	33	34
2	M	107	118	109	111
	SD	17	27	28	25
3	M	113	100	103	105
	SD	25	26	21	25
4	M	105	105	94	101
	SD	37	24	20	28
5	M	112	106	107	109
	SD	24	33	20	26
6	M	103	94	113	103
	SD	31	30	24	29
DAY MEANS	M	110	105	104	GM= 106
	SD	28	31	25	28

TABLE 16

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst time to peak integrated electromyographic activity (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	164	185	174	174
	SD	31	53	43	44
2	M	207	200	197	201
	SD	41	46	39	42
3	M	176	173	172	174
	SD	45	37	28	37
4	M	193	184	191	189
	SD	72	69	56	65
5	M	211	202	190	201
	SD	47	41	34	42
6	M	188	198	197	194
	SD	57	52	39	50
DAY MEANS	M	190	190	187	GM= 189
	SD	52	51	41	48

TABLE 17

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst to the point of maximum acceleration latency (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	1	5	-8	-1
	SD	12	19	18	18
2	M	-2	4	-6	-1
	SD	24	19	23	22
3	M	-8	-6	-21	-12
	SD	39	19	22	29
4	M	-27	-9	-2	-13
	SD	46	38	34	41
5	M	-28	-18	3	-14
	SD	30	27	30	31
6	M	2	11	5	6
	SD	42	36	35	37
DAY MEANS	M	-10	-2	-5	GM= -6
	SD	36	29	29	31

TABLE 18

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst to the specific acceleration-deceleration point of inflexion latency (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	58	64	59	60
	SD	13	13	15	13
2	M	66	60	72	66
	SD	25	13	18	20
3	M	58	61	56	58
	SD	23	16	13	18
4	M	48	55	55	52
	SD	48	18	11	30
5	M	56	62	70	63
	SD	25	28	18	25
6	M	77	77	76	77
	SD	36	33	39	35
DAY MEANS	M	60	63	65	GM= 63
	SD	31	22	22	26

TABLE 19

Means (M) and standard deviations (SD) for the biceps bachii integrated electromyographic silent period (ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	112	97	110	106
	SD	64	35	49	51
2	M	129	127	126	127
	SD	68	56	61	61
3	M	95	86	91	91
	SD	46	41	45	44
4	M	83	111	127	107
	SD	47	42	33	44
5	M	132	143	124	133
	SD	67	53	60	60
6	M	118	118	126	120
	SD	46	49	41	45
DAY MEANS	M	112	114	117	GM= 114
	SD	59	50	50	53

first integrated electromyographic burst duration day means were shown to decrease steadily from day 1 to day 3 during the performance stabilization period (from 147 ms to 135 ms). The day mean standard deviations were also shown to decrease (Table 11). Therefore, practice seems to be responsible for a shortening of the propulsive burst (biceps first burst) producing the studied movement. The triceps brachii burst duration day means remained virtually unchanged during the performance stabilization showing a maximum over all day difference of only 7 ms (table 12). Thus, this parameter does not seem to have been affected by the performance stabilization period. These results are in perfect agreement with Boucher's (1980) and Normand's et al. (1982) results.

The biceps brachii to triceps brachii latencies means and standard deviations are presented in tables 13 and 14. For both these parameters the day means as well as the group means were shown essentially not to change with practice. The variability of the biceps brachii to triceps brachii cocontraction period latency parameter was shown to be much greater than the variability exhibited by the biceps brachii to triceps brachii parameters. This high variability of the biceps brachii to triceps brachii brachii cocontraction pediod latency parameter can be partially explained by the high variability associated with the onset of the triceps cocontraction period (see table

10). Boucher (1980) previously showed that the agonist to antagonist latency decreased with practice, however, the present results failed to demonstrate the same practice effects.

Tables 15 and 16 present the biceps and triceps brachii time to peak integrated electromyographic activity parameters descriptive statistics. For both these parameters all means (day, group and day-group effects) were shown to be very stable during the performance stabilization period. A few previous studies have focused on the time taken by a muscle to reach its peak activity level. (Hirose et al., 1975; McGrain, 1980; Payton et al., 1972; Vorro and Hobart, 1981a, 1981b). These studies tend to agree on the fact that the time to peak activity decreases during skill acquisition. The present results however, are in disagreement with these studies. The triceps brachii burst to the point of maximum acceleration, and to the acceleration-deceleration point of infexion latencies means and standard deviations are displayed in tables 17 and 18. For the triceps brachii burst to the point of maximum acceleration latency (table 17), a negative quantity signifies that the point of maximum acceleration occurred before the onset of the triceps brachii burst. Hence, the sign of the millisecond values found in table 17 gives the order of occurrence of the events monitored. As can be seen in these tables, the means of both parameters exhibited the same pattern or trend (i.e. increasing

from day 1 to day 3) during this three day period. Finally, the means and standard deviations for the twelfth temporal parameter, the biceps brachii silent period are presented in table 19. The duration of the silent period was shown to increase slightly (5 ms) from day 1 to day 3. Furthermore, the variability of this parameter appears to be fairly high, as represented by the high standard deviations.

Since many of the parameters presented above were somewhat novel and quantified according to an original technique, it was sometimes impossible to compare the present results to previous findings. Therefore, the description of the results was often not substantiated with other research data.

Quantitative integrated electromyographic pattern parameters. Tables 20 to 25 present the means and standard deviations for the six quantitative integrated electromyographic pattern parameters. The descriptive statistics for the peak integrated electromyographic activity of the biceps brachii first and second bursts, and triceps brachii burst are presented in tables 20 to 22 respectively. As can be seen in these tables, the peak activity parameters are rather stable, that is, the parameters were unaffected by the practice taking place during the performance stabilization period. The triceps brachii burst

TABLE 20

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst peak activity (mV) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	5.32	4.88	5.19	5.13
	SD	1.54	1.59	1.80	1.64
2	M	5.81	5.69	4.65	5.38
	SD	1.76	1.46	1.05	1.53
3	M	4.34	4.60	5.21	4.72
	SD	2.40	2.29	2.16	2.29
4	M	4.95	5.73	5.35	5.34
	SD	3.28	3.53	2.22	3.05
5	M	4.96	4.05	4.73	4.58
	SD	3.31	2.61	2.86	2.93
6	M	5.05	3.58	5.35	4.66
	SD	2.36	1.30	2.17	2.12
DAY MEANS	M	5.07	4.75	5.08	GM= 4.97
	SD	2.54	2.37	2.10	2.35

TABLE 21

Means (M) and standard deviations (SD) for the biceps brachii seconc integrated electromyographic burst peak activity (mV) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	2.86	2.80	3.01	2.89
	SD	1.41	1.14	1.37	1.30
2	M	2.44	2.31	2.37	2.37
	SD	0.95	0.93	1.06	0.97
3	M	2.34	2.87	2.98	2.73
	SD	1.16	1.32	1.56	1.37
4	M	3.08	3.12	2.48	2.89
	SD	2.34	2.56	1.56	2.19
5	M	2.18	1.98	2.25	2.13
	SD	1.42	1.35	1.56	1.43
6	M	2.17	1.73	2.21	2.04
	SD	1.03	0.69	1.00	0.93
DAY MEANS	M	2.51	2.47	2.55	GM= 2.51
	SD	1.48	1.52	1.39	1.46

TABLE 22

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst peak activity (mV) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS / DAYS		1	2	3	GROUP MEANS
1	M	1.69	1.33	1.54	1.52
	SD	0.82	0.60	0.60	0.69
2	M	1.48	1.54	1.42	1.48
	SD	0.56	0.64	0.70	0.63
3	M	0.78	0.98	1.11	0.96
	SD	0.38	0.61	0.61	0.55
4	M	1.42	1.60	1.64	1.55
	SD	1.14	1.05	0.95	1.04
5	M	0.84	0.96	1.05	0.95
	SD	0.51	0.63	0.67	0.60
6	M	0.51	0.53	0.85	0.63
	SD	0.29	0.20	0.40	0.34
DAY MEANS	M	1.12	1.16	1.27	GM= 1.18
	SD	0.80	0.76	0.72	0.76

TABLE 23

Means (M) and standard deviations (SD) for the slope of the biceps brachii first integrated electromyographic burst (mV/ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	47.9	50.6	54.7	51.1
	SD	18.7	16.6	19.3	18.3
2	M	54.5	51.1	46.6	50.7
	SD	15.0	18.9	20.3	18.3
3	M	44.6	47.3	53.4	48.4
	SD	37.7	20.6	26.0	28.9
4	M	53.8	55.7	57.9	55.8
	SD	24.2	32.0	30.8	28.9
5	M	43.1	41.2	45.1	43.1
	SD	25.4	30.0	28.5	27.7
6	M	53.4	41.2	47.2	47.3
	SD	28.2	19.4	18.8	22.9
DAY MEANS	M	49.5	47.9	50.8	GM= 49.4
	SD	25.9	23.9	24.5	24.8

TABLE 24

Means (M) and standard deviations (SD) for the slope of the triceps brachii integrated electromyographic burst (mV/ms) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS / DAYS		1	2	3	GROUP MEANS
1	M	36.2	28.4	37.8	34.2
	SD	19.8	13.9	21.3	18.8
2	M	25.4	32.7	28.7	28.9
	SD	12.0	21.2	15.0	16.6
3	M	18.1	22.1	24.2	21.5
	SD	12.0	16.9	15.1	14.9
4	M	42.3	46.7	33.2	40.7
	SD	43.6	37.4	29.2	37.2
5	M	18.8	21.7	25.5	22.0
	SD	14.1	14.2	27.6	19.6
6	M	16.6	12.5	16.5	15.2
	SD	16.7	10.6	13.2	13.7
DAY MEANS	M	26.2	27.3	27.7	GM= 27.1
	SD	24.3	23.3	22.0	23.2

TABLE 25

Means (M) and standard deviations (SD) for the integrated electromyographic ratio (mV/mV) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	3.92	4.42	3.82	4.05
	SD	2.26	2.55	2.12	2.31
2	M	4.42	4.24	3.93	4.20
	SD	1.99	1.82	1.80	1.86
3	M	6.61	5.95	5.54	6.03
	SD	3.95	3.98	2.50	3.53
4	M	7.07	5.73	5.63	6.14
	SD	8.91	6.44	6.28	7.26
5	M	5.94	4.46	4.99	5.13
	SD	2.42	1.84	2.60	2.36
6	M	11.79	7.77	7.86	9.14
	SD	7.74	4.69	5.26	6.27
DAY MEANS	M	6.63	5.43	5.29	GM= 5.78
	SD	5.84	4.07	4.01	4.75

peak activity, however, was shown to increase slightly from day 1 to day 3 (0.15 mV or 13% of the initial level). McGrain (1980) measured significant increases in the maximum integrated electromyographic amplitude for two agonist and two antagonist muscles due to skill acquisition. The present results failed to show increases in agonist maximum amplitude, whereas, the antagonist peak activity was shown to increase with practice.

The biceps brachii and triceps brachii integrated electromyographic activity slope data are presented in tables 23 and 24. As for the previous parameters, the slope day means did not seem to be drastically affected by the performance stabilization period. The biceps brachii slope got steeper by 3% of the initial value (1.3 mV/ms) from day 1 to day 3. For the triceps brachii slope, the increase in slope was relatively higher: 6% of the initial value (1.5 mV/ms). Therefore, the triceps brachii slope was shown to increase more from day 1 to day 3 than the biceps brachii slope. McGrain (1980), however, measured significant increases only in agonist muscle myoelectric slope with practice. The antagonist muscle slope was then less affected in this study involving a knee extension task. In the present study, dealing with a forearm flexion movement, the results were opposite. The triceps brachii slope was affected to a greater extent than the biceps brachii slope.

Table 25 presents the last quantitative parameter measured: the integrated electromyographic ratio. As can be seen in table 25, the dominant feature is the high level of variability exhibited by this parameter during the performance stabilization period. For all means, the respective standard deviations are relatively high (i.e., GM = 5.78 and SD = 4.75). Furthermore, over all groups (day means) as well as within groups (day-group interaction) daily practice did not seem to have a great impact upon the mean integrated electromyography ratio. For example, the day means droped of only 1.34 ratio units from day 1 to day 3.

<u>Tension output parameters</u>. The flexion and extension normal and fast maximum tension output means and standard deviations are presented in tables 26 to 29. The descriptive statistics for the flexion normal and fast maximum tension output are found in tables 26 and 27 respectively. As can be seen in these tables, the flexion tension output, fast as well as normal, appeared to be very stable parameters across days. The maximum variations in tension output were of 1.58 pounds from day 1 to day 2 for normal flexion contractions (table 26), and of 1.13 pounds from day 1 to day 2 for fast flexion contractions. The increase in tension output was more noticeable for the extension contractions. From day 1 to day 3, the increase in normal extension contraction tension output was of 3.95 pounds (table 28; from 39.98 to

TABLE 26

Means (M) and standard deviations (SD) for the normal flexion tension output (lbs) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	62.98	59.88	55.36	59.41
	SD	32.76	28.38	26.78	28.74
2	M	35.59	37.14	39.76	37.50
	SD	4.62	8.40	12.36	8.94
3	M	55.95	55.36	57.86	56.39
	SD	10.86	11.28	16.50	12.80
4	M	62.14	66.79	66.19	65.04
	SD	19.99	26.73	26.88	24.12
5	M	46.91	50.95	46.07	47.98
	SD	27.12	25.69	26.40	25.73
6	M	40.24	43.21	45.48	42.98
	SD	13.50	13.92	18.23	15.08
DAY MEANS	M	50.64	52.22	51.79	GM=51.55
	SD	22.44	22.32	22.99	22.49

TABLE 27

Means (M) and standard deviations (SD) for the fast flexion tension output (lbs) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	63.21	58.57	53.69	58.49
	SD	27.94	26.87	25.47	26.30
2	M	37.50	38.21	39.05	38.25
	SD	6.09	7.08	7.59	6.78
3	M	54.76	54.76	59.52	56.35
	SD	13.14	14.21	18.95	15.35
4	M	60.72	66.90	65.36	64.33
	SD	19.98	23.52	22.97	21.73
5	M	50.12	52.26	50.48	50.95
	SD	28.36	24.48	27.06	25.93
6	M	41.43	43.81	44.52	43.25
	SD	9.78	14.92	14.17	12.84
DAY MEANS	M	51.29	52.42	52.10	GM=51.94
	SD	21.09	21.29	21.67	21.26

TABLE 28

Means (M) and standard deviations (SD) for the normal extension tension output (lbs) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	47.14	48.33	51.07	48.85
	SD	8.99	11.55	12.53	10.93
2	M	31.55	26.67	34.05	30.75
	SD	10.20	7.74	8.24	9.08
3	M	47.74	45.36	49.17	47.42
	SD	19.64	16.07	11.90	15.79
4	M	43.10	47.26	50.12	46.83
	SD	13.62	11.50	12.84	12.66
5	M	35.59	40.83	38.33	38.25
	SD	12.49	18.13	11.95	14.21
6	M	34.76	40.83	40.83	38.81
	SD	15.31	13.88	10.45	13.30
DAY MEANS	M	39.98	41.55	43.93	GM=41.82
	SD	14.76	14.99	12.83	14.25

TABLE 29

Means (M) and standard deviations (SD) for the fast extension tension output (lbs) as monitored during the performance stabilization period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS \ DAYS		1	2	3	GROUP MEANS
1	M	48.57	47.50	49.88	48.65
	SD	12.01	10.43	11.07	10.91
2	M	32.50	25.12	34.88	30.83
	SD	9.22	6.46	7.19	8.59
3	M	47.50	43.33	49.64	46.82
	SD	17.95	11.40	13.49	14.36
4	M	44.17	44.76	50.00	46.31
	SD	12.46	9.44	14.73	12.33
5	M	38.21	42.97	41.55	40.91
	SD	11.05	16.61	12.71	13.41
6	M	34.41	43.57	41.91	39.96
	SD	13.49	13.94	11.27	13.21
DAY MEANS	M	40.89	41.21	44.64	GM=42.25
	SD	14.00	13.60	12.89	13.55

43.93). The daily increase in tension output was as marked for the fast contractions: 3.75 pounds from day 1 to day 3 (table 29; from 40.89 to 44.64). Finally, tension output did not seem to be influenced by the modality of contraction producing the tension, that is normal and fast contractions. The present results corroborate previous findings reported by Lagasse (1975, 1979). Lagasse also found that flexion and extension strength was not influenced by practice of a maximum speed forearm flexion movement.

Stimulation parameters. Tables 30 to 35 present the means and standard deviations for six stimulation parameters: the rheobase, single pulse duration and stimulus intensity, for both the biceps and triceps brachii muscles. As can be seen in these tables, the design is not the same as for the previous tables. The stimulation parameters were monitored at the beginning of every treatment session, on which treatments were administered, and not during the test days as for the previous parameters. The stimulation parameters were, thus, collected on each of the 12 treatment sessions. These sessions were divided into two two-weeks periods composed of six treatment days.

As can be seen in table 30, the biceps brachii rheobase appeared to be a very stable parameter. The rheobase did not

TABLE 30

Means (M) and Standard deviations (SD) for the biceps brachii rheobase (Volts). GM: grand mean
Groups: high frequency progression (3), high frequency retrogression (4), low frequency progression (5) and low frequency retrogression (6).

GROUPS	WEEKS		1			2			3			4		GROUP
	DAYS	1	2	3	1	2	3	1	2	3	1	2	3	MEANS
3	M	22.3	21.5	25.5	26.8	26.0	25.7	24.8	29.7	25.3	26.2	26.7	25.8	25.5
	SD	4.8	4.9	4.4	7.2	6.6	4.6	8.4	9.3	9.7	8.8	6.1	4.7	6.6
4	M	29.0	26.3	28.3	31.2	28.5	28.0	26.5	33.5	31.7	32.0	30.3	31.8	29.8
	SD	6.0	5.0	3.7	4.9	6.9	6.4	8.1	6.8	7.8	7.7	7.4	5.0	6.3
5	M	28.3	28.3	25.0	39.0	26.3	27.3	26.3	27.3	25.7	27.5	25.3	28.0	26.5
	SD	9.1	8.1	9.2	7.5	7.9	5.0	7.9	8.5	4.1	7.5	3.3	7.0	6.9
6	M	26.0	28.3	31.3	30.0	32.7	27.5	25.5	29.7	29.3	30.0	29.7	30.2	29.2
	SD	9.3	7.9	3.7	5.7	10.3	8.5	5.0	4.5	6.7	6.2	8.5	6.5	6.9
DAY	M	26.4	26.1	27.5	29.3	28.4	26.5	25.8	30.0	28.0	28.9	28.0	29.0	
MEANS	SD	7.5	6.8	5.9	6.2	8.0	6.0	7.0	7.3	7.4	7.5	6.5	6.0	
WEEK	M		26.7			28.1			27.9			28.6		GM 27.8
MEANS	SD		6.7			6.8			7.3			6.6		6.9

TABLE 31

Means (M) and Standard Deviations(SD) for the biceps brachii single pulse duration (μs). GM: grand mean
Groups: High frequency progression (3), high frequency retrogression (4), low frequency progression (5) and low frequency retrogression (6).

GROUPS	WEEKS		1			2			3			4		GROUP MEANS
	DAYS	1	2	3	1	2	3	1	2	3	1	2	3	
3	M	88	122	185	123	73	119	89	174	100	112	85	93	113
	SD	64	89	167	52	48	47	56	170	42	71	51	45	87
4	M	167	100	265	208	223	283	162	200	158	105	245	242	196
	SD	129	55	330	107	166	254	68	138	60	86	228	169	166
5	M	192	112	102	132	123	272	203	138	122	221	150	119	157
	SD	202	50	43	77	75	277	236	88	139	253	101	112	155
6	M	260	179	228	182	152	298	127	150	120	243	78	64	165
	SD	327	172	331	135	129	143	83	113	75	261	40	35	178
DAY MEANS	M	177	128	195	161	142	218	145	166	125	170	139	129	
	SD	201	101	240	98	120	200	131	124	84	189	138	120	
WEEKD MEANS	M		167			174			145			146	GM	158
	SD		190			148			115			151		153

TABLE 32

Means (M) and Standard deviations (SD) for the biceps brachii stimulus intensity (volts). GM: grand mean
Groups: High frequency progression (3), high frequency retrogression (4), low frequency progression (5) and low frequency retrogression (6).

GROUPS	WEEKS	1			2			3			4			GROUP MEANS
	DAYS	1	2	3	1	2	3	1	2	3	1	2	3	
3	M	35.7	34.3	39.2	40.5	39.7	39.2	38.5	43.7	39.0	39.8	40.5	39.3	39.1
	SD	5.2	5.6	4.8	8.0	7.4	5.1	9.1	10.1	10.5	9.6	6.7	5.2	7.3
4	M	35.2	32.8	36.3	37.0	34.5	34.3	32.7	39.2	37.3	38.0	36.3	37.7	35.9
	SD	5.7	4.4	4.9	4.7	6.3	5.9	7.4	6.1	6.6	6.9	6.8	4.3	5.8
5	M	51.7	51.7	47.8	52.2	49.7	48.3	49.7	50.7	49.0	49.7	48.8	51.3	50.0
	SD	12.2	10.9	13.6	9.5	11.4	6.8	11.7	13.7	10.2	15.4	9.5	12.2	10.8
6	M	44.8	48.5	49.8	47.5	51.0	46.5	43.7	49.3	49.0	49.5	49.3	49.7	48.2
	SD	10.0	13.4	7.4	6.2	12.3	9.7	3.5	3.1	5.8	6.7	9.0	6.1	7.9
DAY MEANS	M	41.8	41.8	43.3	44.3	43.7	42.1	41.1	45.7	43.6	44.3	43.8	44.5	
	SD	10.8	12.1	9.8	9.1	11.4	8.8	10.2	9.8	9.7	11.0	9.4	9.4	
WEEK MEANS	M		42.3			43.4			43.5			44.2		43.3
	SD		10.8			9.7			9.9			9.8		GM 10.1

TABLE 33

Means (M) and Standard deviations (SD) for the triceps brachii rheobase (volts). GM: grand mean
Groups: high frequency progression (3), high frequency retrogression (4), low frequency progression (5) and low frequency retrogression (6).

GROUPS	WEEKS	1			2			3			4			GROUP
	DAYS	1	2	3	1	2	3	1	2	3	1	2	3	MEANS
3	M	21.0	19.3	18.3	20.5	21.8	20.8	23.7	26.5	20.8	24.2	22.5	20.2	21.6
	SD	4.2	3.7	4.6	3.6	4.5	3.6	4.2	6.6	3.6	4.1	3.6	3.1	4.4
4	M	21.5	20.5	21.0	21.7	20.8	23.5	22.2	25.3	26.7	27.5	24.5	25.5	23.4
	SD	3.4	3.5	7.5	6.7	4.6	3.9	4.7	8.8	10.0	7.8	5.9	5.4	6.3
5	M	20.0	19.7	19.0	19.7	20.7	23.7	17.7	20.0	17.0	19.7	19.7	19.2	19.7
	SD	4.0	5.3	3.5	5.3	5.2	7.1	5.0	4.6	6.5	5.7	4.8	5.3	5.1
6	M	21.3	20.0	21.0	22.0	21.0	20.7	21.2	22.3	19.3	21.0	19.0	20.3	20.8
	SD	4.3	5.5	5.8	6.7	5.0	3.9	6.5	5.7	6.0	6.0	6.8	7.8	7.8
DAY	M	21.0	19.9	19.8	21.0	21.1	22.2	21.2	23.5	20.8	23.1	21.4	21.3	
MEANS	SD	3.8	4.3	5.3	5.4	4.5	4.7	5.3	6.7	7.3	6.5	5.5	5.9	
WEEK	M		20.2			21.4			21.8			21.9		GM 21.4
MEANS	SD		4.5			4.9			6.5			5.9		5.5

TABLE 34

Means (M) and Standard deviations (SD) for the triceps brachii single pulse duration (μs). GM: grand mean Groups: high frequency progression (3), high frequency retrogression (4), low frequency progression (5) and low frequency retrogression (6).

GROUPS	WEEKS		1			2			3			4		GROUP
	DAYS	1	2	3	1	2	3	1	2	3	1	2	3	MEANS
3	M	248	292	250	317	417	270	192	200	150	293	233	200	255
	SD	206	191	179	169	242	334	163	352	89	243	166	89	212
4	M	283	375	358	333	175	267	150	150	383	258	233	150	260
	SD	121	113	92	133	94	121	134	122	303	132	144	89	158
5	M	293	433	377	235	242	425	285	275	265	290	353	274	312
	SD	144	207	320	72	142	284	157	82	132	226	297	202	199
6	M	283	245	342	247	277	338	340	400	350	317	243	212	299
	SD	137	99	235	94	77	113	192	268	89	108	98	140	148
DAY	M	277	336	332	283	278	325	242	256	287	290	266	209	
MEANS	SD	146	166	214	123	169	228	170	238	189	175	186	142	
WEEK	M		315			295			262			254	GM	282
MEANS	SD		177			177			199			170		182

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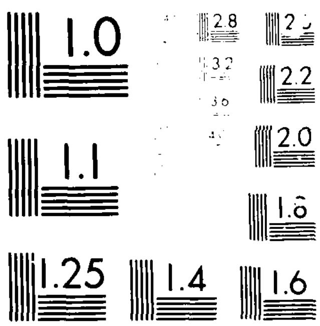
1.0
2.8
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3.2
2.2
3.6
2.0
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1.8
1.25
1.4
1.6

TABLE [illegible]

Means (M) and Standard deviations (SD) for the triceps brachii stimulus intensity (volts). GM: Grand mean
Groups: High frequency progression (3), high frequency retrogression (4), low frequency progression (5)
and low frequency retrogression (6).

GROUPS	WEEKS	1			2			3			4			GROUP MEANS
	DAYS	1	2	3	1	2	3	1	2	3	1	2	3	
3	M	23.8	22.2	21.2	23.3	23.5	23.7	26.3	29.2	23.5	26.8	25.2	22.8	24.3
	SD	4.4	3.9	4.3	4.4	4.5	4.5	4.9	7.0	4.2	4.8	5.4	3.4	4.8
4	M	24.3	23.3	23.8	24.5	23.7	26.3	24.5	27.7	28.5	28.3	26.7	26.7	25.7
	SD	2.3	2.4	7.5	6.9	3.7	3.7	3.7	7.1	3.6	9.3	6.4	6.3	5.9
5	M	31.7	31.7	31.0	31.7	32.7	36.2	29.7	32.0	29.0	31.7	31.7	32.8	31.8
	SD	4.3	5.3	3.5	5.7	5.2	8.0	5.0	4.6	6.5	5.7	4.8	3.5	5.1
6	M	33.3	31.7	33.0	34.0	33.0	32.7	33.2	34.3	31.3	33.0	31.3	32.3	32.8
	SD	4.3	5.9	5.8	6.7	5.0	3.9	6.5	5.9	6.0	6.0	7.1	7.8	5.6
DAY	M	28.3	27.2	27.3	28.4	28.2	29.7	28.4	30.8	28.1	30.0	28.7	28.7	
MEANS	SD	5.7	6.2	7.2	7.2	6.4	7.1	5.9	6.4	6.8	6.7	6.3	6.7	
WEEK	M		27.6			28.8			29.1			29.1		GM 28.6
MEANS	SD		6.3			6.8			6.4			6.5		6.5

seem to be affected by any day or week effects. Furthermore, the variability associated with this parameter is relatively low, which reflects a good homogeneity of the subjects as far as this parameter is concerned. The means and standard deviations for the biceps brachii single pulse duration are presented in table 31. The most striking characteristic of this table is surely the high variability associated with all the means. The standard deviations are often greater than the means themselves. The biceps brachii single pulse duration also exhibited a considerable decrease from the two first weeks to the last two. Hence, the biceps single pulse duration, as monitored in this study, seems to have been affected from the first two-week period to the last. Descriptive statistics for the biceps brachii stimulus intensity are presented in table 32. As for the rheobase, the stimulus intensity appeared to be very stable across all weeks. Some discrepancies, however, can be found between groups. These differences can be explained by the way in which this parameter was derived from rheobase (see Appendix C).

The means and standard deviations for the triceps brachii rheobase are presented in table 33. As for the biceps brachii rheobase, this parameter appeared to be very stable across days. The standard deviations also seemed to be fairly low which reflects again the homogeneity of the subjects. As can be seen in table 34, the variability associated with the triceps brachii

single pulse duration means was found to be very high. Furthermore, the triceps brachii single pulse duration appeared to decrease steadily from the first to the last week: from 315 microseconds for the first week to 254 microseconds for the last week. Finally, table 35 presents the descriptive statistics for the triceps brachii stimulus intensity. For this parameter, as well as for the biceps brachii stimulus intensity (Table 32), discrepancies among group means were assessed. These means ranged from 24.3 volts for the high frequency progression group (group 3) to 32.8 for the low frequency retrogression group (group 6). Here again, these differences are attributable to the way in which the functional electrical stimulation model calculated the stimulus intensity parameter.

Stability

For every parameter the stability of the means over days and trials was assessed using a split-split-plot analysis of variance on the data collected during the performance stabilization period. Tables 36 to 41 present the results of these analyses. As can be seen in these tables, the significance level is always taken to be for a 0.05 probability level.

Kinematic parameters. Table 36 presents a complete analysis of variance table for the analysis of the performance criterion:

TABLE 36

Analysis of variance for the movement time kinematic parameter measured during the performance stabilization period. DF: degrees of freedom. MS: mean squares. F: F ratios.

SOURCES	DF	MS	F
Treatments (G)	35		
G	5	11516.11	1.47
E1 (S:G)	30	7810.11	
Days (D)	72		
D	2	2494.36	4.30*
DG	10	223.08	0.38
E2 (DS:G)	60	579.90	
Trials (T)	432		
T	4	37.61	0.53
TG	20	82.49	1.17
E3 (TS:G)	120	70.71	
TD	8	37.91	0.48
TDG	40	81.64	1.04
E4 (TDS:G)	240	78.78	
Total	539		

*Significant at the 0.05 level.

movement time. The only statistically significant difference found was in the first split-plot (Days) for the day main effect. As can be seen in table 36, the 4.30 F value was greater than the critical F value for the 0.05 confidence level and proper degrees of freedom (DF = 2/60, critical F = 3.15). Therefore, the 8 ms decrease in movement time from the first to the last day represent a significant drop in movement time (see also Figure 9). This significant drop in movement time associated with the day effect corroborates previous finding reported by Boucher (1980) and many others (Finley et al., 1967; Flieger, 1983; Hobart et al., 1975; Kamon et al., 1968; Lagasse, 1975, 1979; Normand et al., 1982; Wolcott, 1977). This drop in movement time represents an expected increase in movement speed which resulted from practice. Therefore, this significant difference due to the day effect should not be associated with a lack of reliability but, rather, an expected practice effect.

The mean squares due to the trial effect (37.61) was much smaller than the mean squares due to the day effect (2494.36), and the trial effect was found not to be statistically significant (F = 0.53). The movement time parameter was then shown to be more stable over trials than over days.

The results of the analyses of variance realized for the last four kinematic parameters are summarized in table 37. As

TABLE 37

Mean squares for the analyses of variance for the kinematic parameters measured during the performance stabilization period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	K2	K3	K4	K5
Treatments (G)	35	1684.99	7959.59	1185.24	6638.13
G	5	1684.99	7959.59	1185.24	6638.13
E1 (S:G)	30	1700.68	3651.51	802.75	3542.25
Days (D)	72				
D	2	2830.16*	543.08	315.87	2918.56
DG	10	313.28	229.79	235.83	1507.69
E2 (DS:G)	60	334.32	344.19	235.07	1183.73
Trials (T)	432				
T	4	111.12	189.69	179.68*	92.92
TG	20	57.61	131.05	37.54	258.01
E3 (TS:G)	120	48.27	85.62	44.44	299.43
TD	8	38.75	79.94	68.62	659.44*
TDG	40	54.15	76.37	43.63	295.68
E4 (TDS:G)	240	50.00	84.80	40.82	274.73
Total	539				

*Significant at 0.05 level.

for the movement time parameter, the time of positive acceleration parameter (K2) was found to decrease significantly over days. Such decrease in this parameter is in accord with results reported by Boucher (1980) who monitored the time of positive acceleration for a maximum speed horizontal arm sweep. Here again, this parameter was shown to be more stable over trials (MS = 111.12) than over days (MS = 28300.16). The percent acceleration time (K3), however, was shown to be stable across days (MS = 543.08) as well as across trials (MS = 189.69).

The stability of this parameter across days, and thus the absence of practice effect, is in disagreement with finding reported by Lagasse (1975) and Wolcott (1977). Both these investigators reported significant practice effects on this parameter when investigating the learning of a maximum speed forearm flexion task in men. Teves (1980), however, studying the same movement in women, failed to observe significant practice effect on the percent acceleration time. For the next kinematic parameter, maximum displacement (K4), a significant trial effect was monitored. Thus, this parameter was more stable over days than over trials. It would then appear that subjects tried different ranges in movement displacement from trial to trial in their learning process. Finally, both the day and trial effects failed to reach the significance level for the time to maximum

acceleration parameter (K5). However, the day effect mean squares for this parameter (2918.56) was greater than the time of positive acceleration parameter (K2) day effect mean squares (2830.16), in which parameter the day effect was statistically significant. The day effect error term (E2 or DS:G mean squares = 1183.73) was much greater for the time to maximum acceleration however. Therefore, not reaching the significance level in this case is more reflective of a greater subject or error variance, or lack of consistency, than a good day stability

Temporal integrated electromyographic pattern parameters. The analyses of variance results for these parameters are presented in table 38. The 4 ms (6%) decrease from the first to the last day for the biceps brachii first burst motor time (T1) was found to be statistically significant (see also Figure 9). Furthermore, the group effect was also found to be significant, which is a puzzling result because all groups were administered the same practice regimen in this performance stabilization period. By looking more closely at the descriptive statistics for this parameter, the differences due to the group effect can be associated with discrepancies in the initial level (day 1). Such between group differences may have been avoided by matching the groups on the basis of this parameter or by increasing the sample size. The triceps brachii integrated electromyographic burst motor time (T2), as well as the triceps brachii

TABLE 38

Mean squares for the analyses of variance for the temporal integrated electromyographic pattern parameters measured during the performance stabilization period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	T1	T2	T3	T4	T5	T6
Treatments (G)	35						
G	5	4390.08*	8826.18	3035.75	1869.95	6035.98	10783.14
E1 (S:G)	30	1507.35	4817.59	3744.30	9300.56	16607.93	7092.85
Days (D)	72						
D	2	687.21*	3342.06	102.16	5999.24*	2390.59	4159.86
DG	10	205.33	1030.36	830.21	3099.22	1325.17	1000.97
E2 (DS:G)	60	194.90	2056.45	1157.03	1224.54	2442.27	1480.31
Trials (T)	432						
T	4	22.21	54.26	203.82	554.82	686.44	162.99
TG	20	105.26	453.52	172.34	472.92	664.63	920.29
E3 (TS:G)	120	87.36	401.55	218.32	672.21	999.91	576.33
TD	8	129.83	291.46	101.00	1252.32*	921.59	392.70
TDG	40	76.27	401.01	268.83	320.51	1047.00	507.14
E4 (TDS:G)	240	99.51	365.30	217.80	426.81	986.36	412.11
Total	539						

*Significant at the 0.05 level.

TABLE 38 (cont.)

SOURCES	DF	T7	T8	T9	T10	T11	T12
Treatments (G)	35						
G	5	4038.28	1201.25	13892.36	6064.26	6191.00	21927.41
E1 (S:G)	30	2358.84	4541.15	17381.54	5063.20	3758.47	23597.70
Days (D)	72						
D	2	263.36	1741.52	637.93	3080.36	828.55	1504.73
DG	10	1538.20	1623.62	1723.80	2809.19	569.31	3795.65
E2 (DS:G)	60	1230.08	1139.40	3633.71	2528.09	1428.43	3277.91
Trials (T)	432						
T	4	106.82	824.31	1909.06	248.15	241.43	526.94
TG	20	249.47	435.44	1446.03	494.59	394.64	768.27
E3 (TS:G)	120	244.54	552.84	807.97	344.96	254.40	1092.24
TD	8	326.06	486.83	877.84	466.59	226.37	1243.56
TDG	40	238.21	301.73	885.16	274.89	263.72	1789.80*
E4 (TDS:G)	240	222.26	419.52	1095.93	404.72	277.60	975.03
Total	539						

*Significant at the 0.05 level.

cocontraction period motor time (T3), did not exhibit any statistically significant practice effect. These results are in opposition with findings reported by Boucher (1980) and Normand et al. (1982). In both these cases, the triceps brachii motor time was found to decrease significantly with practice. In the present study, the 8 ms (15%) decrease in this parameter over days did not reach the level required for significance. However, by examining the mean squares (table 38, T2) it becomes obvious that the day effect error term (E2 or DS:G) is relatively large. Therefore, this parameter not reaching the required significance level is probably due to a low level of within day consistancy. The biceps brachii first integrated electromyographic burst duration (T4) was shown to decrease significantly over days (Figure 9), whereas, the triceps brachii burst duration (T5) was shown to be more stable in time. Boucher (1980) and Normand et al. (1982) both reported the same practice effect on these parameters. Practice of a ballistic movement would, thus, appear to increase the efficiency of the biceps burst without affecting the triceps burst. Both biceps brachii to triceps brachii latencies (biceps to triceps, T6, and biceps to cocontraction period, T7) were shown to be very stable both over days and trials, a finding in accord with data presented by Lagasse (1975) who studied the same experimental movement. Finally, the last five temporal integrated electromyographic parameters (Biceps brachii first burst time to peak activity, T8, triceps brachii

burst time to peak activity, T9, triceps brachii burst to the point of maximum acceleration, T10, triceps brachii burst to the specific acceleration-deceleration point of inflexion, T11, and the biceps brachii silent period, T12) were all shown to be stable over days and over trials. It would therefore appear that the parameters relative to the biceps brachii integrated electromyographic activity (i.e., T1 and T4) were more affected by practice than parameters relative to the triceps brachii burst.

Quantitative integrated electromyographic pattern parameters. Table 39 presents the results of the analyses of variance realized on the quantitative integrated pattern parameters: biceps brachii first burst peak activity (Q1), biceps brachii second burst peak activity (Q2), triceps brachii burst peak activity (Q3), slope of the biceps brachii first burst (Q4), slope of the triceps brachii burst (Q5) and the integrated electromyographic ratio (Q6).

For the peak activity parameters (Q1, Q2 and Q3), all the variances or mean squares associated with the day and trial effect were found to be relatively low. No statistically significant day or trial effects were found for these three parameters. Therefore, traditional practice would have the effect of modifying some temporal components of the integrated

TABLE 39

Mean squares for the analyses of variance for the quantitative integrated electromyographic pattern parameters measures during the performance stabilization period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	Q1	Q2	Q3	Q4	Q5	Q6
Treatments (G)	35						
G	5	11.67	12.98	13.53*	1630.96	7879.07	313.38
E1 (S:G)	30	56.04	24.12	4.63	6145.93	3564.83	170.41
Days (D)	72						
D	2	6.21	0.29	1.04	395.85	99.04	96.63
DG	10	10.34	2.03	0.53	476.40	654.56	22.31
E2 (DS:G)	60	6.61	1.85	0.79	681.02	465.23	35.22
Trials (T)	432						
T	4	1.81	0.22	0.09	55.75	329.98	4.07
TG	20	1.75	0.57	0.12	190.48	120.73	7.70
E3 (TS:G)	120	1.51	0.45	0.14	247.33	358.68	5.67
TD	8	2.15	0.80	0.19	228.36	80.84	6.63
TDG	40	1.55	0.71	0.13	153.10	241.45	7.97
E4 (TDS:G)	240	1.71	0.55	0.10	211.09	214.71	7.12
Total	539						

*Significant at the 0.05 level.

electromyographic pattern without affecting these quantitative parameters. These results are in total disagreement with findings reported by McGrain (1980). McGrain concluded that when temporal electromyographic changes are not evident over practice, increases in maximum integrated electromyographic amplitude of muscles are responsible for increasing performance proficiency. Both the biceps brachii first burst and triceps brachii burst slopes (Q4 and Q5) exhibited low day and trial effects mean squares. These parameters were then very stable during the practice period, which is again opposite to the finding reported by McGrain (1980). Finally, the integrated electromyographic ratio appeared to be even more stable across days and across trials. The mean squares associated with the day (96.63) and trial (4.07) main effects were found to be very low, and so were the mean squares associated with their respective error terms (E2 Ms = 35.22 and E3 MS = 5.67).

<u>Tension output parameter</u>. The mean squares for all sources of variation for all four tension output parameters are presented in table 40. The four tension output parameters monitored were the peak tension output for flexion isometric maximum voluntary contractions, under normal (TO1) and fast (TO2) conditions, and extension isometric maximum contractions also under normal (TO3) and fast (TO4) conditions. During all four conditions two trials

TABLE 40

Mean squares for the analyses of variance for the tension output parameters measured during the performance stabilization period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	TO1	TO2	TO3	TO4
Treatments (G)	35				
G	5	3965.73	3452.66	1800.54	1553.52
E1 (S:G)	30	2666.04	2427.06	924.71	794.53
Days (D)	72				
D	2	48.38	24.48	284.56*	311.34*
DG	10	88.55	103.47	71.46	124.28
E2 (DS:G)	60	113.76	75.82	72.05	66.54
Trials (T)	108				
T	1	136.01*	9.10	78.27*	218.21*
TG	5	13.84	6.71	31.53*	17.16
E3 (TS:G)	30	11.95	15.98	12.27	13.09
TD	2	4.88	6.51	7.67	0.46
TDG	10	7.68	5.56	9.76	18.26
E4 (TDS:G)	60	8.11	14.32	10.08	18.83
Total	215				

*Significant at the 0.05 level.

PARAMETERS	DAY MEANS		
K1	D3	D2	D1
K2	D3	D2	D1
T1	D3	D2	D1
T4	D3	D2	D1
TO3	D1	D2	D3
TO4	D1	D2	D3

Figure 9. Results of the Duncan post hoc analysis for the parameters that exhibited significant day main effect during the performance stabilization period. D1, D2 and D3: Testing days ranked according to mean value. Significant at the 0.05 level.

were executed and, therefore, the trials split-plot degrees of freedom were different in the tension output parameter analyses of variance when compared to all other parameters presented above.

For the flexion tension output parameters (TO1 and TO2) the mean squares were generally lower for the fast condition (TO2). This was true especially for the trial effect. A statistically significant trial effect was found for the normal flexion tension output (TO1 trial MS = 136.01), whereas, the fast flexion tension output trial effect was very low (TO2 trial MS = 9.10). Both these parameters were very stable across days. Lagasse (1975) and Wolcott (1977) both reported fairly stable strength parameters across days. The results are different for the extension tension output parameters (TO3 and TO4). In both parameters, the day and trial effects were found to be statistically significant. As shown on figure 9, the difference was shown to occur mostly in the last pre-test day. It appeared that the extension tension output parameters were less stable across days and trials than the flexion tension output parameters.

Stimulation parameters. The stimulation parameters analyzed were the biceps brachii rheobase (SP1), single pulse duration (SP2) and stimulus intensity (SP3), and the triceps brachii

rheobase (SP4), single pulse duration (SP5) and stimulus intensity (SP6). These parameters were collected at the beginning of every treatment session (i.e., 4 treatment weeks with 3 treatment sessions or days per week). Therefore, even though the design utilized for these parameters is still a split-split-plot design, it is different from the one utilized for the previous parameters. The major components of this design were then the treatments or groups (whole-plot, DF = 23), the weeks (first split-plot, DF = 72) and the treatment sessions or days (second split-plot, DF = 192).

All stimulation parameters were found to be very stable across weeks and days (Table 41). No statistically significant differences were found for these main effects for all parameters monitored. The treatment or group effect was found to be statistically significant for both the biceps brachii and triceps brachii stimulus intensity. However, these differences were to be expected because of the way in which the stimulus intensity was derived from the functional electrical stimulation model (see Appendix C). Furthermore, for the triceps brachii rheobase (SP4) and stimulus intensity (SP6) the day-week interaction (DW) was found statistically significant. These parameters then appeared to be more stable across weeks than within weeks even though the over all day effect was not statistically significant.

TABLE 41

Mean squares for the analyses of variance for the stimulation parameters. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	SP1	SP2	SP3	SP4	SP5	SP6
Treatments (G)	23						
G	3	283.92	175.84	3391.82*	175.11	94.84	1310.68*
E1 (S:G)	20	262.32	135.33	492.56	226.12	81.44	223.07
Weeks (W)	72						
W	3	47.65	68.74	41.82	44.61	52.66	37.51
WG	9	20.25	150.84	19.88	44.60	52.15	33.35
E2 (WS:G)	60	40.76	112.16	63.11	24.41	50.02	26.19
Days (D)	192						
D	2	7.39	160.99	18.46	7.44	0.29	3.25
DG	6	17.22	167.51	24.33	19.66	18.53	19.83
E3 (DS:G)	40	19.72	127.27	22.86	9.69	36.17	9.58
DW	6	55.79	145.43	53.25	29.76*	49.12	29.10*
DWG	18	15.32	122.79	16.09	5.83	27.19	6.21
E4 (DWS:G)	120	26.41	121.42	27.08	7.57	31.52	8.30
Total	297						

*Significant at the 0.05 level.

Consistency

The consistency of all the parameters monitored was assessed through an analysis of variance intraclass correlation model. The reliability and/or consistency of all parameters was then analyzed in terms of the true score, day and trial variance estimates as well as the intraclass reliability coefficient (R). These variance estimates along with the intraclass reliability coefficient for all parameters are presented in table 42.

Kinematic parameters. The intraclass reliability coefficients ranged from good to excellent ($R = 0.71 - 0.92$) for all kinematic parameters. The highest among the kinematic parameters reliability coefficient ($R = 0.92$) was the one for the performance criterion, movement time (K1). This high coefficient was due to a high true score variance (TRUE = 417.10) compared to relatively low day (DAY = 61.34) and trial (TRIAL = 63.41) variance estimates. The day and trial variance estimates were of same magnitude, which indicated that the movement time was as consistent from trial to trial as from day to day. For all the other kinematic parameters the trial variance was much greater than the day variance. Also in all other cases, as for movement time, the day and trial variances were lower than the true score variance.

TABLE 42

Variance estimates and intraclass reliability coefficients (R) for all parameters. TRUE: true score variance. DAY: day variance. TRIAL: trial variance.

PARAMETERS	TRIAL	DAY	TRUE	R
Kinematic				
K1	63.41	61.34	417.10	0.92
K2	129.72	57.47	228.80	0.85
K3	58.32	13.89	60.64	0.83
K4	38.60	29.91	45.13	0.71
K5	262.47	131.05	262.12	0.74
Temporal				
T1	98.78	14.27	131.56	0.89
T2	328.44	98.13	342.87	0.81
T3	239.02	141.49	129.22	0.58
T4	422.87	196.98	473.91	0.77
T5	916.73	123.48	979.26	0.86
T6	427.89	97.33	431.02	0.82
T7	225.56	107.94	89.27	0.54
T8	419.22	59.48	318.94	0.82
T9	864.27	303.84	1019.07	0.81
T10	353.57	304.15	177.04	0.49
T11	242.82	46.99	212.61	0.82
T12	985.30	384.44	1145.66	0.80
Quantitative				
Q1	1.56	0.76	2.80	0.84
Q2	0.57	0.26	1.33	0.88
Q3	0.12	0.05	0.40	0.92
Q4	220.24	23.17	353.21	0.91
Q5	274.31	25.11	217.72	0.84
Q6	5.80	2.47	8.21	0.82

TABLE 42 (cont.)

PARAMETERS	TRIAL	DAY	TRUE	R
Tension Output				
TO1	12.47	27.23	480.43	0.97
TO2	11.56	24.61	431.41	0.97
TO3	11.31	30.15	156.66	0.90
TO4	20.22	30.53	129.50	0.86

PARAMETERS	DAY	WEEK	TRUE	R
Stimulation				
SP1	24.41	4.69	18.89	0.86
SP2	12.54	0.00	2.17	0.18
SP3	25.81	10.34	67.83	0.94
SP4	8.92	6.29	15.98	0.87
SP5	31.90	6.16	2.73	0.39
SP6	9.33	6.08	28.11	0.93

These consistency results are in agreement with values that can be found in the maximum speed of movement literature. Boucher (1980), Flieger (1983), Lagasse (1975,1979) and Wolcott (1977) all reported intraclass reliability coefficients for movement time ranging from 0.88 to 0.96. The magnitude of the true score variance in this study (417.10), however, is more comparable to the one reported by Flieger(TRUE = 582.57) than the one reported by Lagasse (TRUE = 214.00) and Wolcott (TRUE = 174.68). These discrepancies in the magnitude of the true score variance could reside in the fact that both Lagasse's and Wolcott's experiments involved only male subjects, whereas, in the present study and in Flieger's investigation a sample of both male and female subjects were involved. Furthermore, the trial variance estimate found in this study (TRIAL = 63.41) is almost identical to the one reported by Flieger (TRIAL = 65.07). These trial variance estimates are much greater than the one presented by Wolcott (TRIAL = 16.72). This last difference can be explained by the very nature of the movement investigated. In Wolcott's study a class A movement was studied, the subjects did not have to stop on target. However, by restricting the movement amplitude and increasing the demands in term of accuracy in a class B movement, such as the one studied herein, replication of the movement may have been more difficult.

Temporal integrated electromyographic pattern parameters. The intraclass reliability coefficients for the temporal parameters ranged from fair to good (R = 0.49 - 0.89). From the 12 temporal parameters, nine of these exhibited reliability coefficients above 0.77 whereas the other three presented coefficients lower than 0.60. In these three last cases (T3, T7 and T10), the low reliability coefficient can be associated with low true score variance. These three parameters represent the only three instances where the true score variance was lower than both the day and trial variance estimates. These three parameters with low true score variances and reliability coefficient are all triceps brachii activity related and they are: the brachii cocontraction period motor time (T3), the biceps brachii to triceps brachii cocontraction period latency (T7) and the triceps brachii to the point of maximum acceleration latency (T10).

As stated previously, all other temporal parameters exhibited high reliability coefficients (R = 0.77 - 0.89). These results corroborate reliability findings reported by Lagasse and Hayes (1973) and Lagasse (1975, 1979). Finally, the integrated electromyography quantification software program developed for this study appeared to yield satisfactory results.

Quantitative integrated electromyographic pattern parameters. All quantitative parameters (Q1 to Q6) presented high intraclass reliability coefficient ($R = 0.82 - 0.92$). The three peak activity parameters (Q1, Q2 and Q3) presented relatively low variance estimates, and in these cases the trial variance was higher than the day variance. Thus, peak integrated electromyographic activity seemed easier to duplicate from one day to the other than between trials. The slope parameters (Q4 and Q5) exhibited the highest variance estimates of all the quantitative parameters. In both these parameters the trial variance was 10 times greater than the day variance. Hence, these parameters would be much more consistent from day to day than trial to trial. The slope parameters could be defined as an indirect measurement of the rate of recruitment of faster and bigger motor units. Therefore, from one trial to the other the pattern of motor unit recruitment in both the biceps and triceps brachii muscles may differ greatly.

The last quantitative parameter, the integrated electromyographic ratio (Q6), was also shown to be a very consistent parameter in time. The trial variance (TRIAL = 5.80) was also found to be twice as great as the day variance (DAY = 2.47), which represents a higher consistency between day than

between trials. Since most of the quantitative parameters, including this last one, represent novel integrated electromyographic information quantified according to an original method, it was often hard to compare the present results to other research endeavors.

Tension output parameters. As can be seen on table 42, the tension output parameter reliability coefficient ranged from good to excellent (R = 0.86 - 0.97). Both the normal and fast flexion tension output parameters (TO1 and TO2) exhibited very high intraclass reliability coefficient of R = 0.97. These high coefficient are due to very high true score variances as compared to low day and trial variance estimates. For the same two parameters the day variance was found to be twice as great than the trial variance indicating that subjects could easily repeat a contraction from one trial to the other but not so for day to day. The coefficients for the normal and fast tension output parameters (TO3 and TO4) were a little lower (R = 0.90 and 0.86). The major factor that contributed to lowering these coefficients is most probably the relatively small true score variance (TRUE = 156.66 and 129.50). The true score variances for the extension tension output parameters were four times smaller than the flexion parameters, whereas, the day and trial variance estimates were of comparable magnitude. The high reliability of maximum isometric strength has been demonstrated on several occasions.

Therefore, the results of the present investigation concerning the reliability of the tension output parameters were to be expected.

Stimulation parameters. The standardization of the functional electrical stimulation pattern was realized in this study by the development of the functional electrical stimulation model (Appendix C). This model evaluates the functional electrical stimulation pattern parameters based upon the values of the stimulation parameters rheobase and single pulse duration. The reliability of the stimulation parameters becomes then essential to the utilization of the functional electrical stimulation model.

The six stimulation parameters were divided into two sets (biceps and triceps brachii muscles) of three parameters (rheobase, single pulse duration and stimulus intensity). Both the biceps brachii rheobase (SP1) and triceps brachii rheobase (SP4) were found to be highly consistent parameters (R = 0.86 and 0.87). For both these parameters the week variance was very low (WEEK = 4.69 and 6.29). The day variance for the biceps brachii rheobase (DAY = 24.41) was relatively high, even higher than the true score variance (TRUE = 18.89), whereas, the day variance for the triceps brachii rheobase was considerably lower (DAY = 8.92).

Therefore, both parameters appeared to be very consistent from week to week, and the longer term consistency of these parameters seems to be assured. However, from day to day the biceps brachii rheobase may vary.

The single pulse duration parameters (SP2 and SP5) yielded the smallest intraclass reliability parameters (R = 0.18 and 0.39) of all parameters monitored. In both the biceps brachii single pulse duration (SP2) and the triceps brachii single pulse duration (SP5), the true score and week variance were very low and the day variances very high. Therefore, the low reliability coefficients do not really reflect a lack of reliability but they rather are the result of a double contribution of a subject consistency (low true score variance) and high day inconsistency (high day variance). Finally, the high reliability exhibited by the biceps brachii stimulus intensity (SP3, R = 0.94) and triceps brachii stimulus intensity (SP6, R = 0.93) were expected because of the way in which they are derived from their respective rheobase (Appendix C). The only noticeable difference between the variance estimates of the rheobase and stimulus intensity is in the increase in the true score variance for the stimulus intensity parameter. According to the functional electrical stimulation model, the stimulus intensity was to be increased by 10% in the progression groups and reduced by 10% in the

retrogression groups. The utilization of this model had the effect of increasing the between groups differences, and thus increase the true score variance.

Experimental Treatment Effects

The five testing days (three pre-tests and two post-tests) were divided into two independent periods for analysis purposes. The data collected on the first period, the performance stabilization period composed of the three pre-tests, were presented above. The reliability analyses performed on these data were also presented. The object of this section is to present the data collected during the treatment period (the last pre-test and two post-tests). As presented above the 27 parameters monitored and analyzed herein are as follows: five kinematic, 12 temporal and six quantitative integrated electromyographic pattern, and four tension output parameters.

The first part of this section presents the descriptive statistics of all parameters for the day, group (or treatment) and day-group effects. Whereas, the second part presents the results of the split-split-plot analysis of variance performed on all parameters measured during the treatment period. During the

performance stabilization period all subjects regardless of the group, executed the same practice regimen (i.e., 15 trials per day for three days without between day treatments). Therefore, the analyses performed on the data collected on that period reflected the practice or performance stabilization effects occurring from the first pre-test (day 1) to the last pre-test (day 3). For that reason the reliability analyses were executed on that period. However, during the treatment period, several experimental treatments were administered to the subjects of the different groups. Thus, the analyses presented below served not only to detect the treatment effects occurring across days but also to compare the different treatments (or groups) between them.

Descriptive statistics

Kinematic parameters. Tables 43 to 47 present the means and standard deviations for the five kinematic parameters.

TABLE 43

Means (M) and standard deviations (SD) for the movement time (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	131	131	128	130
	SD	17	15	15	15
2	M	144	129	128	134
	SD	18	9	8	14
3	M	128	130	133	131
	SD	15	16	16	16
4	M	136	130	127	131
	SD	31	20	20	24
5	M	149	144	150	148
	SD	24	28	33	29
6	M	149	146	144	146
	SD	17	12	15	15
DAY MEANS	M	139	135	135	GM= 136
	SD	22	19	21	21

TABLE 44

Means (M) and standard deviations (SD) for the time of positive acceleration (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	105	100	103	103
	SD	15	18	14	16
2	M	117	114	114	115
	SD	20	13	10	15
3	M	108	106	108	107
	SD	12	15	12	13
4	M	112	117	110	113
	SD	19	68	13	41
5	M	125	122	127	125
	SD	10	12	19	14
6	M	118	114	109	113
	SD	20	17	15	17
DAY	M	114	112	112	GM= 113
MEANS	SD	18	32	16	23

TABLE 45

Means (M) and standard deviations (SD) for the percent acceleration time (%) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	81.0	76.8	81.0	79.6
	SD	12.1	11.9	13.0	12.3
2	M	81.8	88.4	89.1	86.4
	SD	13.1	9.8	6.5	10.6
3	M	84.8	81.6	81.5	82.6
	SD	9.9	11.0	11.0	10.7
4	M	84.5	88.5	87.7	86.9
	SD	13.5	34.8	9.2	22.0
5	M	85.2	86.6	85.7	85.8
	SD	10.5	10.7	8.6	9.9
6	M	79.9	78.5	76.0	78.1
	SD	15.5	11.7	10.8	12.8
DAY MEANS	M	82.9	83.4	83.5	GM= 83.3
	SD	12.6	17.8	10.9	14.0

TABLE 46

Means (M) and standard deviations (SD) for the maximum displacement (degrees) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	117	111	112	113
	SD	10	9	8	9
2	M	116	117	113	115
	SD	13	7	8	9
3	M	114	110	111	112
	SD	10	10	11	11
4	M	108	108	112	109
	SD	10	12	8	10
5	M	111	111	110	111
	SD	6	10	10	9
6	M	116	109	108	111
	SD	8	8	8	9
DAY MEANS	M	114	111	111	GM= 112
	SD	10	10	9	10

TABLE 47

Means (M) and standard deviations (SD) for the time to maximum acceleration (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	88	94	87	90
	SD	27	17	20	22
2	M	88	89	105	94
	SD	23	12	19	20
3	M	76	92	82	83
	SD	22	13	11	17
4	M	80	89	98	89
	SD	21	22	25	23
5	M	101	102	93	99
	SD	27	23	14	22
6	M	97	91	98	95
	SD	23	19	17	20
DAY MEANS	M	88	93	94	GM= 92
	SD	25	19	19	21

As can be seen in table 43, the over all day movement time means decreased by 4 ms from day 1 to day 3. However, if one looks more closely at the day-group means and the groups means, one can notice that the variation of the means across day differed between groups (table 43). The day-group means for the practice group (group 2), for instance, decreased 15 ms from day 1 to day 2 and of 1 ms from day 2 to day 3. Whereas, the day-group means increased steadily from day 1 to day 3 for the high frequency progression group (group 3). The groups were then influenced differently by the different treatments. These results corroborate many previous investigations that noted the facilitatory effects of practice and functional electrical stimulation (Boucher, 1980; Boucher and Lagasse, 1981; Fleury and Lagasse, 1979; Lagasse et al., 1979; Vodovnik, 1971a).

Tables 44 and 45 present the time of positive acceleration and the percent acceleration time parameters data respectively. As can be seen in these tables, the over all grand mean (GM) for the time of positive acceleration was 113 ms, and the percent acceleration time grand mean was 83.3%. For both parameters, the day means as well as the day-group means appeared to be very stable. The time of positive acceleration decreased only 2 ms from day 1 to day 2, whereas, the percent of acceleration time

increased only 0.6%. Therefore, the movement time decreased with treatment without noting any major modification in the acceleration pattern of the movement, which suggests that muscle coordination was modified in order to act on the movement time (Kroll et al., 1982).

The fourth kinematic parameter, maximum displacement, appeared to be as unchanging as the two previously cited parameters (table 46). Very little variation was observed among the day means, group means and/or day-group means. Furthermore, for all means the coefficient of variation was very low (CV 10%), which is indicative of the high consistency of the maximum displacement parameter. Differently, the time to maximum acceleration appeared to be a variable parameter, that is, the standard deviations were relatively high (table 47). Therefore, this parameter was deemed more stable than consistent.

Temporal integrated electromyographic pattern parameters.

Tables 48 to 59 show the data for the 12 integrated electromyographic pattern parameters. The biceps first burst motor time did not seem to be affected by the treatments occurring from day 1 to day 3 (table 48). This motor time was 64 ms, 61 ms and 63 ms for days 1, 2 and 3 respectively. The same stability can be observed within the groups in the day-group

TABLE 48

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst motor time (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	58	56	57	57
	SD	10	13	14	12
2	M	70	65	65	67
	SD	15	14	10	13
3	M	60	57	58	59
	SD	12	9	8	10
4	M	56	56	59	57
	SD	15	15	13	14
5	M	72	63	72	69
	SD	14	9	13	13
6	M	70	70	69	70
	SD	23	13	10	16
DAY MEANS	M	64	61	63	GM= 63
	SD	17	13	13	14

TABLE 49

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst motor time (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	37	33	36	35
	SD	14	18	13	15
2	M	48	29	26	34
	SD	25	8	11	19
3	M	37	39	45	41
	SD	20	19	21	20
4	M	46	39	41	42
	SD	23	16	15	18
5	M	55	40	54	49
	SD	21	32	31	29
6	M	60	44	48	51
	SD	46	12	22	31
DAY MEANS	M	47	37	42	GM= 42
	SD	28	19	22	23

TABLE 50

Means (M) and standard deviations (SD) for the triceps brachii cocontraction period motor time (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	26	33	33	31
	SD	26	22	34	28
2	M	46	29	17	30
	SD	16	21	25	24
3	M	31	20	33	28
	SD	20	31	17	24
4	M	33	15	31	26
	SD	12	33	17	24
5	M	35	16	35	29
	SD	19	35	27	29
6	M	43	25	33	34
	SD	31	17	13	23
DAY MEANS	M	36	23	30	GM= 30
	SD	22	28	24	25

TABLE 51

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst duration (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	133	138	138	136
	SD	29	31	28	29
2	M	152	137	137	142
	SD	27	18	20	23
3	M	135	138	141	138
	SD	24	25	31	27
4	M	119	121	120	120
	SD	23	25	20	22
5	M	130	145	131	136
	SD	22	35	31	30
6	M	141	142	141	141
	SD	34	25	26	28
DAY MEANS	M	135	137	135	GM= 135
	SD	28	28	27	28

TABLE 52

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst duration (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	102	107	97	102
	SD	45	52	43	47
2	M	112	96	95	101
	SD	29	25	20	26
3	M	114	89	93	99
	SD	48	36	44	44
4	M	104	76	100	93
	SD	51	60	50	55
5	M	95	91	107	98
	SD	36	31	36	35
6	M	118	84	110	104
	SD	61	26	37	46
DAY MEANS	M	108	90	100	GM= 99
	SD	46	41	39	43

TABLE 53

Means (M) and standard deviations (SD) for the biceps brachii to triceps brachii integrated electromyographic latency (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	155	153	153	154
	SD	23	24	25	24
2	M	162	167	163	164
	SD	22	19	12	18
3	M	153	152	150	152
	SD	17	20	16	17
4	M	142	145	152	146
	SD	32	27	31	30
5	M	168	176	163	169
	SD	23	18	17	20
6	M	162	175	166	168
	SD	46	22	22	32
DAY MEANS	M	157	161	158	GM= 159
	SD	29	25	22	26

TABLE 54

Means (M) and standard deviations (SD) for the biceps brachii to triceps brachii cocontraction period latency (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	34	26	27	29
	SD	22	19	28	23
2	M	27	38	48	38
	SD	17	20	20	21
3	M	37	41	32	36
	SD	20	28	20	23
4	M	26	38	30	31
	SD	13	24	16	19
5	M	37	48	43	43
	SD	12	30	14	20
6	M	27	45	37	36
	SD	26	21	16	22
DAY MEANS	M	31	39	36	GM= 36
	SD	19	25	21	22

TABLE 55

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst time to peak integrated electromyographic activity (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	100	105	100	102
	SD	33	30	25	29
2	M	109	115	112	112
	SD	28	23	12	22
3	M	103	97	107	102
	SD	21	29	27	26
4	M	94	98	93	95
	SD	20	27	19	22
5	M	107	115	105	109
	SD	20	29	27	26
6	M	113	117	114	114
	SD	24	25	31	27
DAY MEANS	M	104	108	105	GM= 106
	SD	25	28	25	26

TABLE 56

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst time to peak integrated electromyographic activity (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	174	182	174	177
	SD	43	50	58	51
2	M	197	192	177	189
	SD	39	47	25	39
3	M	172	157	166	165
	SD	28	39	31	33
4	M	191	137	159	162
	SD	56	40	37	50
5	M	190	182	183	185
	SD	34	50	40	42
6	M	197	179	190	189
	SD	39	29	32	34
DAY MEANS	M	187	171	175	GM= 178
	SD	41	46	40	43

TABLE 57

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst to the point of maximum acceleration latency (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	-8	-5	-13	-9
	SD	18	15	14	16
2	M	-6	-15	7	-4
	SD	23	14	23	22
3	M	-21	-1	-10	-11
	SD	22	24	21	24
4	M	-2	-2	12	3
	SD	34	21	19	26
5	M	3	-10	3	-1
	SD	30	27	20	27
6	M	5	-14	1	-3
	SD	35	18	22	27
DAY MEANS	M	-5	-8	0	GM= -4
	SD	29	21	22	24

TABLE 58

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst to the specific acceleration-deceleration point of inflexion latency (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	59	61	57	59
	SD	15	13	11	13
2	M	72	64	64	66
	SD	18	13	9	14
3	M	56	58	51	55
	SD	13	13	12	13
4	M	55	55	59	56
	SD	11	14	8	11
5	M	70	57	66	65
	SD	18	25	21	22
6	M	76	53	59	63
	SD	39	12	15	27
DAY MEANS	M	65	58	59	GM= 61
	SD	22	16	14	18

TABLE 59

Means (M) and standard deviations (SD) for the biceps brachii integrated electromyographic silent period (ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	110	110	99	106
	SD	49	50	55	51
2	M	126	124	111	120
	SD	61	43	29	46
3	M	91	67	96	85
	SD	45	25	44	41
4	M	127	123	102	117
	SD	33	41	36	38
5	M	124	99	97	107
	SD	60	55	41	54
6	M	126	113	74	104
	SD	41	35	27	41
DAY MEANS	M	117	106	96	GM= 106
	SD	50	46	41	47

means. The group means, however, seem to be more discrepant. The differences observed in the group means (ranging from 57 ms to 70 ms) can also be observed in the six day 1 day-group means (ranging from 56 ms to 72 ms). Thus, the discrepancies monitored in the group means could be associated with the initial level of that parameter and not to treatment or group differences. The stability of the agonist muscle motor time, even during functional electrical stimulation treatment, is in accord with previous findings reported by Boucher (1980) and Fleury and Lagasse (1979).

The triceps brachii burst and cocontraction period motor times means and standard deviations can be found in tables 49 and 50 respectively. Both these parameters showed peculiar day mean trends. In both instances, there was a sharp decrease in motor time from day 1 to day 2 and an increase from day 2 to day 3. It would thus appear, as pointed out by Boucher (1980), that during treatment the antagonist muscle activity is more susceptible to modifications. Furthermore, the variability associated with these parameters is high as revealed by the high standard deviations. For both parameters, the group means appeared to be relatively more stable or to show less differences among them.

Tables 51 and 52 present the biceps brachii and triceps brachii burst durations means and standard deviations. As for

the previous two parameters, the triceps brachii burst duration group means showed fewer discrepancies than the day means, which day means presented the same peculiar trend: decreased (18 ms) from day 1 to day 2 and increased (10 ms) from day 2 to day 3 (table 52). Both the day and group means for the biceps brachii burst duration did not show much differences. Again for these parameters, the triceps brachii burst seem to have been more affected by the treatment period than the biceps brachii burst.

Tables 53 and 54 present the descriptive statistics for the biceps brachii to triceps brachii bursts latency and the biceps brachii to triceps brachii cocontraction period latency respectively. For all means presented in these tables, the biceps brachii to triceps brachii bursts latency standard deviations were relatively lower than the standard deviations for the biceps brachii burst to triceps brachii cocontraction period latency. The standard deviations for both these parameters were of the same magnitude; however, the biceps brachii to triceps brachii bursts latency means were four to five times greater than the biceps brachii burst to triceps brachii cocontraction period latency means. The time to peak integrated electromyographic parameters for the first biceps brachii burst and the triceps brachii burst means and standard deviations are presented in tables 55 and 56 respectively. When comparing both parameters it appeares that the biceps burst time to peak activity was more

stable over days than the triceps burst time to peak activity. Here again, the triceps brachii parameter was more affected by treatments than the biceps brachii parameters. Furthermore, even though the triceps brachii burst time to peak activity decreased drastically over days, it was still 70 ms longer than the biceps brachii burst time to peak activity. Thus, it would seem that the biceps brachii muscle produced a peak contraction at a faster rate of motor unit recruitment than for the triceps brachii muscle.

The descriptive statistics for the triceps brachii integrated electromyographic burst to the point of maximum acceleration latency parameter are presented in table 57. Here again the negative values indicate that the point of maximum acceleration occurred before the onset of the triceps brachii burst. As can be seen in table 57, the day and day-group means tendency is to increase from day 1 to day 3, while the standard deviation decreased over days. Therefore, it appeared that with treatments (from day 1 to day 3) the triceps brachii burst onset would overlap or come before the point of maximum acceleration. Hence, the relationship between the triceps brachii muscle activity and the movement acceleration pattern would seem to be modified from day 1 to day 3. The means and standard deviations for the triceps brachii burst to the specific acceleration-deceleration point of inflexion latency parameter

are shown in table 58. As can be seen in this table, this latency decreased from day 1 to day 2, from 65 ms to 58 ms, whereas it remained practically constant from day 2 to day 3 (58 ms to 59 ms). The same day mean pattern (a sharp decrease followed by a levelling-off or increase) can be recognized in the day-group means within different groups. More precisily, in the practice control group (group 2), the low frequency progression group (group 5), and the low frequency retrogression group (group 6), a similar day-mean trend can be observed. Very few differences can be found in the group means for this parameter.

Finally, the biceps brachii silent period parameter data can be found in table 59. First the standard deviations for the means presented in this table are fairly high. The coefficient of variation varied from 30% to 50%. Furthermore, the standard deviations appeared to decrease over days, relealing that the groups became more homogeneous over days with experimental treatment. A second noticeable feature is the steady decrease of the silent period from day 1 to day 3. The silent period was reduced by 11 ms from day 1 to day 2 and by 10 ms from day 2 to day 3. The same decrease can be observed within most of the groups (i.e.: groups 2, 4, 5 and 6). Finally, in the group means, only the high frequency progression group mean was much lower than the rest of the groups. This discrepancy, however, can be attributed to the low initial level in that specific group

(group 3).

<u>Quantitative integrated electromyographic pattern parameters</u>. Tables 60 to 65 present the descriptive statistics for the six quantitative integrated electromyographic pattern parameters. The descriptive statistics for the first quantitative electromyographic parameter, the biceps first burst peak activity, are presented in table 60. Two prominent features are to be noticed: (1) the small range of all means, and (2) the relatively high standard deviations. For example, the day means increased only by 0.26 mV from day 1 to day 3, and the day means standard deviations ranges from 2.10 mV to 3.36 mV. Therefore, the increase in peak activity from day 1 to day 3 is much lower than the experimental error as represented by the standard deviations.

Table 61 displays the means and standard deviations for the biceps brachii second burst peak activity. The day means for this parameter shows a steady increase from day 1 to day 3. This day means pattern, however, is not recognizable in the day-group means within the different groups. The day means pattern varied drastically from one group to the other. Within the control group (group 1) the peak activity decreased from day 1 to day 2 and increased from day 2 to day 3, whereas, the pattern was

TABLE 60

Means (M) and standard deviations (SD) for the biceps brachii first integrated electromyographic burst peak activity (mV) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	5.19	4.40	4.87	4.82
	SD	1.80	1.88	1.52	1.75
2	M	4.65	7.62	6.37	6.21
	SD	1.05	5.73	2.03	3.73
3	M	5.21	4.62	5.19	5.01
	SD	2.16	3.08	2.65	2.65
4	M	5.35	6.06	5.92	5.78
	SD	2.22	2.54	3.26	2.70
5	M	4.73	3.41	3.31	3.82
	SD	2.86	1.62	1.78	2.23
6	M	5.35	5.24	6.34	5.64
	SD	2.17	1.94	1.62	1.97
DAY MEANS	M	5.08	5.23	5.34	GM= 5.21
	SD	2.10	3.36	2.44	2.69

TABLE 61

Means (M) and standard deviations (SD) for the biceps brachii second integrated electromyographic burst peak activity (mV) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	3.01	2.23	3.23	2.82
	SD	1.37	1.03	1.72	1.45
2	M	2.37	4.13	3.25	3.25
	SD	1.06	3.15	0.82	2.08
3	M	2.98	2.99	2.88	2.95
	SD	1.56	1.29	1.17	1.34
4	M	2.48	3.01	3.63	3.04
	SD	1.56	2.04	2.77	2.21
5	M	2.25	3.47	2.84	2.85
	SD	1.56	2.94	1.77	2.21
6	M	2.21	2.80	4.87	3.29
	SD	1.00	1.28	2.33	1.99
DAY MEANS	M	2.55	3.10	3.45	GM= 3.03
	SD	1.39	2.17	1.98	1.91

TABLE 62

Means (M) and standard deviations (SD) for the triceps brachii integrated electromyographic burst peak activity (mV) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	1.54	1.42	1.52	1.50
	SD	0.60	0.74	0.52	0.62
2	M	1.42	1.63	1.93	1.66
	SD	0.70	0.54	0.78	0.71
3	M	1.11	0.85	1.53	1.16
	SD	0.61	0.42	1.07	0.80
4	M	1.64	1.52	1.71	1.62
	SD	0.95	0.96	1.16	1.02
5	M	1.05	0.99	1.21	1.08
	SD	0.67	0.64	0.97	0.77
6	M	0.85	0.81	0.85	0.84
	SD	0.40	0.24	0.26	0.31
DAY MEANS	M	1.27	1.20	1.46	GM= 1.31
	SD	0.72	0.71	0.91	0.79

TABLE 63

Means (M) and standard deviations (SD) for the slope of the biceps brachii first integrated electromyographic burst (mV/ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	54.7	43.8	53.1	50.6
	SD	19.3	20.1	24.5	21.8
2	M	46.6	66.6	56.9	56.7
	SD	20.3	48.9	15.5	32.5
3	M	53.4	47.8	50.2	50.4
	SD	26.0	24.5	27.5	25.8
4	M	57.9	63.7	65.9	62.5
	SD	30.8	29.4	35.9	32.0
5	M	45.1	32.7	33.9	37.2
	SD	28.5	24.3	21.4	25.2
6	M	47.2	46.5	60.9	51.5
	SD	18.8	18.4	25.7	22.0
DAY MEANS	M	50.8	50.2	53.5	GM= 51.5
	SD	24.5	31.3	27.4	27.9

TABLE 64

Means (M) and standard deviations (SD) for the slope of the triceps brachii integrated electromyographic burst (mV/ms) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS \ DAYS		1	2	3	GROUP MEANS
1	M	37.8	32.0	39.1	36.3
	SD	21.3	27.5	23.4	24.1
2	M	28.7	36.2	33.9	32.9
	SD	15.0	27.7	16.6	20.6
3	M	24.2	23.7	40.2	29.4
	SD	15.1	15.4	25.7	20.7
4	M	33.2	67.1	47.5	49.3
	SD	29.2	52.1	33.8	41.6
5	M	25.5	23.8	29.0	26.1
	SD	27.6	20.8	28.9	25.8
6	M	16.5	19.5	16.9	17.7
	SD	13.2	10.5	10.1	11.3
DAY MEANS	M	27.7	33.7	34.4	GM= 31.9
	SD	22.0	32.7	25.9	27.3

TABLE 65

Means (M) and standard deviations (SD) for the integrated electromyopgraphic ratio (mV/mV) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	3.82	4.38	3.51	3.90
	SD	2.12	3.76	1.66	2.66
2	M	3.93	4.59	3.77	4.09
	SD	1.80	2.45	1.61	1.99
3	M	5.54	7.21	5.50	6.08
	SD	2.50	6.14	6.53	5.37
4	M	5.63	6.78	5.49	5.97
	SD	6.28	5.31	5.42	5.65
5	M	4.99	4.95	4.77	4.90
	SD	2.60	3.48	4.86	3.72
6	M	7.86	7.01	8.10	7.66
	SD	5.26	3.27	3.69	4.14
DAY MEANS	M	5.29	5.82	5.19	GM= 5.43
	SD	4.01	4.37	4.57	4.32

reversed for the practice control group (group 2). Furthermore, the peak activity remained relatively unchanged from day 1 to day 3 for the high frequency progression group (group 3), while it increased sharply from day 2 to day 3 in the low frequency retrogression group (group 6). Thus, the modification occurring in this parameter seems to be specific to the treatment administered. In opposition the day means trend for the triceps burst peak activity (table 62) can be readily observed within all groups, with the exception of the control practice group (group 2). Therefore, for this last parameter the day effect seemed independent of the treatment administered. Finally, a comparison of the three peak activity parameters revealed that the peak activity for the two biceps brachii bursts were three to five times higher than for the triceps brachii burst peak activity.

The biceps brachii and triceps brachii bursts integrated electromyographic slope parameters means and standard deviations can be found in tables 63 and 64 respectively. The dominant feature of the biceps brachii burst slope means was the stability. The day means, as well as other means, did not show any drastic discrepancy among them. However, the situation is totally different for the triceps brachii burst slope. For this parameter, there was a noticeable increase from day 1 to day 2 and a levelling off from day 2 to day 3. This over all day means

pattern is, however, not really representative of the individual group day means patterns. For instance, groups 1, 3 and 5 showed a decrease in the slope from day 1 to day 2 and an increase from day 2 to day 3. Therefore, the modifications occurring in this parameter in the day-group means seem to be related to the treatments. Finally, table 65 presents the integrated electromyographic ratio means and standard deviations. The standard deviations associated with all the integrated electromyographic ratio means were remarkably high. On the other hand, the means were very stable between days, that is over all groups as well as within groups. Finally, the modification occurring with treatments in the quantitative parameters is somewhat in agreement with McGrain's results (1980). McGrain, however, did find modifications in the amplitude and slope of both agonist and antagonist muscles. In this study, the triceps brachii muscle activity appeared to be more affected during the treatment period than the biceps brachii activity.

Tension output parameters. The descriptive statistics for all four tension output parameters are presented in tables 66 to 69. High standard deviations were common to all means of all parameters. Furthermore, the flexion as well as the extension maximum tension output, fast and normal, appeared to be very stable. No major differences could be observed between days or between groups. The biggest difference in maximum tension output

TABLE 66

Means (M) and standard deviations (SD) for the normal flexion tension output (lbs) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	55.36	59.29	62.86	59.17
	SD	26.78	27.37	30.28	27.55
2	M	39.76	38.57	39.76	39.37
	SD	12.36	9.24	9.76	10.25
3	M	57.86	53.93	55.71	55.83
	SD	16.50	17.25	11.53	14.95
4	M	66.19	66.19	70.95	67.78
	SD	26.88	24.44	23.68	24.42
5	M	46.07	45.48	46.90	46.15
	SD	26.40	24.31	22.19	23.66
6	M	45.48	39.88	43.57	42.98
	SD	18.23	14.95	14.42	15.67
DAY MEANS	M	51.79	50.56	53.29	GM=51.88
	SD	22.99	22.32	22.27	22.45

TABLE 67

Means (M) and standard deviations (SD) for the fast flexion tension output (lbs) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	53.69	56.91	62.98	57.86
	SD	25.47	24.46	27.79	25.49
2	M	39.05	38.57	37.26	38.29
	SD	7.59	7.36	6.74	7.07
3	M	59.52	57.86	57.62	58.33
	SD	18.95	20.15	13.73	17.33
4	M	65.36	66.31	72.38	68.02
	SD	22.97	24.15	23.39	23.04
5	M	50.48	48.69	50.83	50.00
	SD	27.06	24.32	25.64	24.97
6	M	44.52	40.12	45.24	43.29
	SD	14.17	12.39	15.51	13.86
DAY MEANS	M	52.10	51.41	54.39	GM=52.63
	SD	21.67	21.68	22.69	21.95

TABLE 68

Means (M) and standard deviations (SD) for the normal extension tension output (lbs) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS	DAYS	1	2	3	GROUP MEANS
1	M	51.07	49.17	52.26	50.83
	SD	12.53	13.71	21.01	15.77
2	M	34.05	32.62	37.14	34.60
	SD	8.24	9.57	14.30	10.86
3	M	49.17	46.67	40.95	45.60
	SD	11.90	17.70	20.01	16.76
4	M	50.12	46.19	42.02	46.11
	SD	12.84	15.12	7.98	12.45
5	M	38.33	45.48	42.86	42.22
	SD	11.95	21.33	19.56	17.81
6	M	40.83	44.76	44.52	43.37
	SD	10.45	10.71	13.86	11.58
DAY MEANS	M	43.93	44.15	43.29	GM=43.79
	SD	12.83	15.63	16.81	15.11

TABLE 69

Means (M) and standard deviations (SD) for the fast extension tension output (lbs) as monitored during the experimental treatment period. GM: grand mean. Groups: passive control (1), practice control (2), high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6).

GROUPS \ DAYS		1	2	3	GROUP MEANS
1	M	49.88	48.93	50.12	49.64
	SD	11.07	13.50	17.07	13.70
2	M	34.88	37.14	36.55	36.19
	SD	7.19	12.63	13.10	11.01
3	M	49.64	46.55	40.24	45.48
	SD	13.49	17.60	16.15	15.88
4	M	50.00	46.43	40.59	45.67
	SD	14.73	12.59	7.47	12.29
5	M	41.55	45.72	43.69	43.65
	SD	12.71	21.68	18.96	17.73
6	M	41.91	44.28	44.28	43.49
	SD	11.27	10.90	14.02	11.85
DAY MEANS	M	44.64	44.84	42.58	GM=44.02
	SD	12.89	15.19	15.00	14.37

was observed between the flexion and extension contractions. The normal flexion maximum tension output grand mean was established at 51.88 lbs, as compared to 43.79 lbs for the extension maximum tension output grand means. Thus, there was a difference of almost 10 lbs between the two modalities.

Treatment effect analyses

This study proposed principally to address the two following questions: (1) what are the effects of functional electrical stimulation treatments upon the neuromuscular coordination control mechanisms (day effect); and (2) what are the effects of different functional electrical stimulation treatment conditions (treatment or group effect). This section presents the results obtained in an effort to answer these questions. These results were derived from analyses of variance performed on the parameters monitored during the treatment period.

Kinematic parameters. The complete analysis of variance table for the performance criterion, movement time (K1), is presented on table 70. The day main effect was the only one to be statistically significant ($F = 3.83$). The 4 ms decrease from day 1 to day 3 (table 43) was found to be significant (see also Figure 10). Boucher (1980) among others (Lagasse et al., 1979; Liberson et al., 1961) reported improvement of a specific

movement following functional electrical stimulation or practice. Therefore, following the three days performance stabilization period, movement time was shown to decrease over the two two-week treatment periods.

The results (mean squares only) for the analyses of variance for the last four kinematic parameters (time of positive acceleration, K2, percent acceleration time, K3, maximum displacement, K4, and time to maximum acceleration, K5) are presented in table 71. As can be seen in this table, no statistically significant differences were assessed in the whole-plot (treatments or groups) and the first split-plot (days) for all four kinematic parameters. Thus, the treatment period had no further statistically significant effect upon these parameters. The only two statistically different effects that can be found in table 71 are for the trial-group and trial-day interactions for the maximum displacement (K4) parameter. Maximum displacement is a measurement of movement accuracy, or how far past the 90-degree target the subjects stopped the movement. Hence, it appeared that the trial to trial movement strategy (how far to stop) was influenced by the specific groups assigned, and by the test day.

<u>Temporal integrated electromyographic pattern parameters</u>. Table 72 presents the results of the analyses of variance for all

TABLE 70

Analysis of variance for the movement time kinematic parameter measured during the treatment period. DF: degrees of freedom. MS: mean squares. F: F ratios.

SOURCES	DF	MS	F
Treatments (G)	35		
G	5	6147.83	1.20
E1 (S:G)	30	5139.53	
Days (D)	72		
D	2	1123.98	3.83*
DG	10	536.26	1.83
E2 (DS:G)	60	293.18	
Trials (T)	432		
T	4	70.86	1.22
TG	20	43.74	0.75
E3 (TS:G)	120	58.04	
TD	8	58.95	1.05
TDG	40	43.29	0.77
E4 (TDS:G)	240	55.90	
Total	539		

*Significant at the 0.05 level.

TABLE 71

Mean squares for the analyses of variance for the kinematic parameters measured during the treatment period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	K2	K3	K4	K5
Treatments (G)	35				
G	5	5078.25	1266.22	347.34	2671.35
E1 (S:G)	30	2824.39	1106.43	602.33	2181.01
Days (D)	72				
D	2	280.52	21.10	475.16	1468.72
DG	10	226.77	205.36	167.50	1434.85
E2 (DS:G)	60	494.92	222.82	164.97	1284.20
Trials (T)	432				
T	4	263.66	67.87	15.40*	116.54
TG	20	271.50	90.35	74.44	185.45
E3 (TS:G)	120	357.47	138.30	40.15	162.85
TD	8	332.68	118.24	74.53*	208.34
TDG	40	298.79	113.10	40.48	153.17
E4 (TDS:G)	240	301.43	113.07	37.64	165.26
Total	539				

*Significant at the 0.05 level.

TABLE 72

Mean squares for the analyses of variance for the temporal integrated electromyographic pattern parameters measured during the treatment period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	T1	T2	T3	T4	T5	T6
Treatments (G)	35						
G	5	3392.99*	4150.57	572.42	5819.33	1308.39	8007.14
E1 (S:G)	30	1198.88	3557.43	3338.73	5119.33	14256.01	3408.37
Days (D)	72						
D	2	470.57	4432.24*	7220.18*	223.44	13233.51*	846.92
DG	10	155.49	999.94	1935.85	901.06	2915.65	582.84
E2 (DS:G)	60	362.58	808.90	1754.49	911.04	2056.63	1002.54
Trials (T)	432						
T	4	101.72	135.93	152.88	63.38	472.36	118.28
TG	20	38.35	397.32	224.89	333.49	922.01	442.13
E3 (TS:G)	120	84.66	275.09	228.51	389.57	952.81	351.65
TD	8	57.23	210.95	304.96	437.90	1094.16	432.74
TDG	40	78.22	269.39	243.71	282.65	1102.48	405.16
E4 (TDS:G)	240	76.45	202.68	226.44	392.98	788.72	293.77
Total	539						

*Significant at the 0.05 level.

TABLE 72 (cont.)

SOURCES	DF	T7	T8	T9	T10	T11	T12
Treatments (G)	35						
G	5	2207.32	4785.33	12410.21	2138.18	1973.03	14027.36
E1 (S:G)	30	1949.01	3387.67	11771.07	2471.56	1681.80	15572.45
Days (D)	72						
D	2	2956.55	609.83	11769.04*	3045.41	2255.08*	19621.17*
DG	10	1198.99	386.58	3835.75	2210.93	939.59	4997.41
E2 (DS:G)	60	1264.29	1034.84	2864.50	1708.60	528.25	3117.09
Trials (T)	432						
T	4	12.90	188.56	1248.13	82.55*	192.80	1174.41
TG	20	134.39	463.06	485.90	369.76	232.95	820.55
E3 (TS:G)	120	204.58	415.61	845.62	212.87	181.07	692.58
TD	8	248.59	259.49	997.05*	434.03	182.11	620.10
TDG	40	232.42	358.21	1326.84	252.65	174.40	811.87
E4 (TDS:G)	240	238.31	419.55	711.19	222.36	135.13	907.19
Total	539						

*Significant at the 0.05 level.

temporal parameters measured during the treatment period. The group main effect was found to be statistically significant only for the biceps brachii first burst motor time (T1). However, as stated above, the discrepancies that were found in the over all group means can be observed in the day 1 day-group means (table 48, day 1 day-group means ranging from 56 ms to 72 ms). Therefore, it seems that the statistically significant group effects for the biceps brachii first burst motor time (T1) is due to a residual effect from the performance stabilization period and not a treatment period effect.

For the day split-plot an interesting feature is noticeable. Five of the six parameters which exhibited a significant day effect were all triceps brachii related parameters. The triceps brachii burst motor time (T2), cocontraction period motor time (T3), duration (T5), time to peak activity (T9), and its latency with respect to the specific acceleration-deceleration point of inflexion (T11) were found to yield statistically significant day effects. The only biceps brachii parameter to show a significant day effect was the biceps brachii silent period (T12). Furthermore, a Duncan post hoc analysis (Figure 10) revealed that in most cases a significant difference existed only between the highest (day 1) and the lowest (day 2 or day 3) day means. Boucher (1980) previously reported that agonist muscle burst durations were affected by

functional electrical stimulation and practice, whereas, antagonist muscle burst duration was not. Boucher also reported that agonist muscles motor times were not affected while the antagonist muscle motor time was. Therefore, in that previous study, the target muscle as well as the parameter made a difference in whether or not functional electrical stimulation had an effect. In this study, however, the target muscle only seems to dictate if a given parameter will be influenced by the treatments. In other words, modelled functional electrical stimulation seems to have more specific effects on the maximum speed forearm flexion movement components.

The significant decrease in the biceps brachii silent period from day 1 to day 3 (table 59) represents an interesting finding. In the performance stabilization period, where practice alone was administered to the subjects, the silent period was found to increase slightly from day 1 to day 3 (table 19). In the treatment period, when different functional electrical stimulation treatments were introduced, the silent period was shown to significantly decrease from day 1 to day 3 (table 59, from 117 ms on day 1 to 96 ms on day 3). Furthermore, when observing the day-group means more closely, it seemed that the different treatments (or groups) influenced this parameter differently. The biceps brachii silent period, which is a measurement of the muscle coordination and/or co-activation, was

then influenced differently by different treatments.

Quantitative integrated electromyographic pattern parameters. The mean squares for the analyses of variance for the quantitative integrated electromyographic pattern parameters measured during the treatment period can be found in table 73. As can be seen in this table, none of these parameters exhibited a significant treatment or group main effect. For all parameters, except for the triceps brachii burst slope (Q5) and the integrated electromyographic ratio (Q6), the mean squares for the group main effect was almost equal or lower than the mean squares for the error term (E1 or S:G).

As for the day effects, three quantitative parameters were found to vary significantly across days: the biceps brachii second burst peak activity (Q2), the triceps brachii burst peak activity (Q3), and the triceps brachii burst slope (Q5). Here again, the results of the Duncan post hoc analysis can be found in figure 10. Out of these three parameters, two exhibited significant day-group interactions (Q2 and Q5).

These results are partially in accord with McGrain's findings (1980). McGrain studied, among other parameters, the maximum integrated electromyographic amplitude and the slope from

TABLE 73

Mean squares for the analyses of variance for the quantitative integrated electromyographic pattern parameters measured during the treatment period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	Q1	Q2	Q3	Q4	Q5	Q6
Treatments (G)	35						
G	5	65.55	3.58	9.93	6361.65	10148.85	181.59
E1 (S:G)	30	58.72	30.50	6.13	5898.45	4818.80	94.00
Days (D)	72						
D	2	2.98	37.20*	3.20*	545.55	2498.05*	20.57
DG	10	21.14	14.78*	0.62	1521.18	2006.16*	9.00
E2 (DS:G)	60	14.70	7.52	0.65	1254.02	771.31	50.22
Trials (T)	432						
T	4	0.35	1.15*	0.27	176.96	81.73	15.55
TG	20	1.52	1.36	0.21	248.45	170.87	7.46
E3 (TS:G)	120	1.62	0.72	0.15	283.04	313.71	7.03
TD	8	2.04	0.64	0.16	148.87	216.60	10.18
TDG	40	1.50	0.67	0.09	193.59	325.75	5.13
E4 (TDS:G)	240	1.67	0.89	0.11	288.84	333.28	7.70
Total	539						

*Significant at the 0.05 level.

initial myoelectric activity to maximum amplitude in two agonist muscles and two antagonist muscles involved in a four-wheeled carriage propelling task. The carriage was propelled along a level aluminum track by a knee extension movement. The performance criterion in that task consisted of reproducing a target carriage velocity of 15 mph (6.71 m/s). Following practice the maximum amplitude was shown to increase for all muscles whereas the slopes significantly increased only for the agonist muscles. In the present study, the peak activity, or maximum amplitude for McGrain, was shown to increase across days in all integrated electromyographic bursts monitored (but not statistically significant for the first biceps brachii burst), which is consistent with McGrain's findings. However, the integrated electromyographic slope parameter was found to increase significantly only for the triceps brachii burst (the antagonist muscle). These results are, therefore, opposed diametrically to the ones presented by McGrain. Finally, since these parameters are somewhat original and measured in a specific experimental design, it was often hard if not impossible to corroborate the present findings with previous data.

Tension output parameters. Table 74 presents the results of the analyses of variance performed on the four tension output parameters: the flexion normal (TO1) and fast (TO2) contractions, and the extension normal (TO3) and fast (TO4) contractions. As

TABLE 74

Mean squares for the analyses of variance for the tension output parameters measured during the treatment period. DF: degrees of freedom. (see text for parameter descriptions)

SOURCES	DF	T01	T02	T03	T04
Treatments (G)	35				
G	5	4249.32	4292.47	1046.10	707.09
E1 (S:G)	30	2718.22	2565.28	1111.51	1053.20
Days (D)	72				
D	2	135.49	174.52*	14.15	112.95
DG	10	55.93	79.52*	140.72	105.84
E2 (DS:G)	60	54.42	38.29	128.07	110.37
Trials (T)	108				
T	1	83.50*	41.20	7.96	87.07*
TG	5	13.17	2.45	15.74	21.91
E3 (TS:G)	30	13.24	22.65	16.70	12.01
TD	2	11.39	4.17	5.56	7.14
TDG	10	10.74	8.85	8.10	4.44
E4 (TDS:G)	60	13.41	15.39	12.39	12.12
Total	215				

*Significant at the 0.05 level.

PARAMETERS	DAY MEANS		
K1	D3	D2	D1
T2	D2	D3	D1
T3	D2	D3	D1
T5	D2	D3	D1
T9	D2	D3	D1
T11	D2	D3	D1
T12	D2	D3	D1
Q2	D1	D2	D3
Q3	D2	D1	D3
Q5	D1	D2	D3
TO2	D2	D1	D3

Figure 10. Results of the Duncan post hoc analysis for the parameters that exhibited significant day main effect during the experimental treatment period. D1, D2 and D3: Testing days ranked according to mean value. Significant at the 0.05 level.

for the previous parameters, none of the tension output parameters yielded a significant group main effect. Furthermore, the day main effect and day-group (DG) interaction were found to be significant only in the fast flexion tension output parameters (TO2). A Duncan post hoc analysis revealed that only the last day mean was significantly greater than the two other day means (Figure 10). It appeared that the increase in isometric tension output followed a slow process that occurred only at the end of the treatment period. These results are somewhat surprising and hard to interpret because of the low intensity of stimulation. At higher levels of stimulation intensity increases in strength have been reported (Kots, 1971). However, the goal of the present study was not to test for the strengthening effect of functional electrical stimulation but rather to test for the possible role of this technique in sensory imparted learning. Therefore, the increase in fast flexion tension output appeared as a secondary effect of the treatments and/or the testing schedule.

Performance Predictability

This section of the study was designed to test for the effects of performance stabilization and/or modification upon its predictability. As mentionned several times, the performance

criterion was the speed of movement as measured through the movement time parameter. Hence, the object of this section was to attempt to predict movement time from the pool of measurement criteria presented above. The prediction of movement time was realized on the data of the first and last day of the performance stabilization period.

Performance predictability was approached by first studying the intercorrelation structure of the data collected on day 1 and day 3 of the performance stabilization period. Then, a forward and backward stepwise linear multiple regression model was utilized in an effort to predict movement time.

Intercorrelation structure

The intercorrelation matrix for all 27 parameters monitored (K1 to K5, T1 to T12, Q1 to Q6, and TO1 to TO4) is presented in table 75. In the upper diagonal of this matrix is presented the non redundant Pearson correlation coefficients for the data collected on the first day (day 1) of the performance stabilization period. The lower diagonal presents the Pearson correlation coefficients for the day 3 data. Table 75 is then a compact presentation of 702 possible non redundant Pearson correlation coefficients. In order to help the interpretation of this table, it was divided into six major components: two vectors

TABLE 75

Intercorrelation matrix.

PARAMETERS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1- K1	--	76	-41	-23	20	59	50	35	49	36	56	-02	27	70	-33	00	21	-28	-40	-46	-43	-50	14	-63	-63	-66	-65
2- K2	57	--	27	-20	-06	59	32	40	32	35	58	-12	00	73	-58	-14	41	-26	-55	-48	-31	-46	14	-46	-46	-50	-47
3- K3	-60	31	--	06	-36	-06	-17	07	-31	-03	-11	-17	-44	-06	-24	-11	30	00	-24	-02	20	10	-04	31	32	34	34
4- K4	-16	-15	00	--	34	-21	-32	-07	-15	-04	-10	-03	08	-03	24	24	-28	12	38	46	05	40	-20	00	-03	-05	-10
5- K5	44	30	-24	38	--	00	-15	-22	08	-12	-19	-27	33	07	49	13	05	08	10	13	-10	00	-10	-26	-24	-26	-22
6- T1	58	23	-44	08	33	--	26	35	22	25	54	18	27	48	-26	12	32	-27	-43	-45	-45	-51	14	-50	-48	-36	-36
7- T2	69	47	-33	-38	-04	49	--	53	11	52	-28	-41	-08	22	16	50	13	-40	-46	-49	-25	-42	18	-31	-32	-19	-26
8- T3	33	05	-31	-10	-13	64	50	--	16	61	-01	-80	02	61	-06	31	-16	-43	-19	-46	-36	-32	22	-37	-43	-27	-31
9- T4	49	-07	-66	26	35	56	10	30	--	41	46	-01	59	49	-42	-34	-18	-24	-14	-09	-50	-25	01	-31	-21	-26	-26
10- T5	57	31	-36	-03	03	39	66	36	38	--	-03	-53	07	52	-06	19	-22	-42	-22	-32	-38	-41	14	-35	-40	-23	-28
11- T6	61	19	-53	21	57	63	01	12	69	10	--	33	34	63	-66	-58	16	-15	-23	-27	-42	-34	06	-32	-31	-31	-27
12- T7	04	08	00	26	46	14	-26	-62	08	-14	43	--	19	-31	-07	-25	27	23	-02	21	04	04	-24	19	25	07	14
13- T8	48	-10	-67	18	41	50	11	25	79	29	62	10	--	28	-04	06	-15	10	17	21	-40	-07	08	-26	-25	-28	-28
14- T9	63	32	-40	-07	23	46	33	57	50	52	50	-34	37	--	-48	-13	-02	-31	-29	-36	-46	-53	11	-54	-56	-52	-51
15-T10	18	29	06	27	66	29	16	11	00	16	-01	15	17	03	--	64	-13	09	22	19	19	18	-10	04	05	06	04
16-T11	42	29	-21	06	10	43	74	55	17	47	-12	-37	20	16	37	--	10	06	00	-05	09	-09	07	-30	-31	-28	-36
17-T12	18	58	35	-04	35	04	-01	-02	-16	-23	10	08	-19	13	39	-01	--	06	-66	-20	12	-29	03	-11	-04	-06	-06
18- Q1	-29	-30	05	21	21	-20	-44	-28	-04	-33	03	29	12	-20	07	-21	-04	--	56	50	82	32	15	03	05	-10	-05
19- Q2	-42	-68	-18	28	-11	-13	-38	-14	02	-14	-07	15	16	-28	-15	-16	-70	61	--	57	39	67	-06	14	12	02	07
20- Q3	-57	-28	41	12	-18	-39	-45	-31	-36	-42	-31	07	-28	-33	-07	-25	07	39	41	--	36	74	-54	21	23	16	19
21- Q4	-52	-25	37	08	-05	-45	-46	-35	-41	-45	-32	17	-37	-37	-05	-26	06	87	47	51	--	32	15	17	19	06	09
22- Q5	-58	-30	39	05	-24	-44	-44	-45	-45	-58	-32	20	-33	-60	-18	-31	-03	37	44	85	51	--	-43	37	37	25	32
23- Q6	31	06	-31	-17	43	27	00	10	38	13	35	16	43	16	36	-01	02	25	-03	-28	00	-50	--	-14	-16	-11	-13
24-TO1	-72	-35	53	-34	-51	-44	-33	23	-70	-43	-60	-05	-61	-48	-19	-41	-07	20	24	45	47	52	-30	--	98	70	75
25-TO2	-69	-32	52	-37	-52	-41	-29	-19	-70	-40	-58	-05	-62	-45	-19	-40	-08	17	21	37	44	46	27	98	--	70	75
26-TO3	-63	-33	46	-33	-55	-44	-33	-14	-65	-33	-50	-13	-54	-31	-33	-48	-15	18	25	34	43	43	-26	85	85	--	96
27-TO4	-57	-27	44	-42	-51	-47	-29	-13	62	-31	-46	-13	52	-25	-36	-48	-15	17	19	23	41	34	-21	82	84	98	--

n = 36, critical r value for the 0.05 confidence level: $r_{0.05} = 0.339$

and four submatrices. The two vectors, the first row and the first column of the matrix, represent the correlation coefficients of movement time with all other parameters. The four submatrices outlined in the table represent the intercorrelation matrices for the kinematic parameters, the temporal and quantitative integrated electromyographic pattern parameters, and the tension output parameters.

After a first overview of the intercorrelation matrix it was found that 116 correlation coefficients of the upper diagonal (Day 1) were significant, whereas, 170 were found to be significant in the lower diagonal (Day 3). Out of all these significant correlation coefficients, only 12 of the coefficients of the upper diagonal and 14 of the lower diagonal were above 0.70 (or 50% of common variance). In both the upper and lower diagonals, the six tension output parameter correlation coefficients, and the two correlation coefficients relating the integrated electromyographic slope and peak activity for both the biceps and triceps brachii, were above 0.70. In order to look at the intercorrelation matrix in greater details, its components were approached separately.

<u>Movement time vectors</u>. As noted above, the movement time vectors (the first row and first column) represent the correlation coefficients for the movement time with all other

parameters for the day 1 (first row) and day 3 (first column) data. In each vector, 18 out of 26 coefficients, reached the significance level for the day 1 vector and 20 reached it for the day 3 vector.

It was not surprising to find a significant positive correlation coefficient between movement time (K1) and the time of positive acceleration (K2) in both vectors. Similarly, significant negative correlation coefficients were found between the movement time (K1) and the percent acceleration time (K3) for both vectors. The correlation coefficients of -0.41 and -0.60 found between movement time and percent acceleration time on day 1 and day 3 respectively, are comparable to the ones reported by Flieger (1983) and Wolcott (1977). Lagasse (1975), however, reported a coefficient of -0.80 between the two same parameters, which is much higher. Furthermore, a drastic increase in these coefficients was observed from day 1 to day 3. The correlation coefficient between movement time and percent acceleration time went from -0.41 on day 1 to -0.60 on day 3. It is important to note that in the other findings reported above (Flieger, 1983; Lagasse, 1975, 1979; Wolcott, 1977) the data for correlation analysis were collected on well practiced individuals. Furthermore, the -0.60 correlation coefficient assessed on day 3 data is in the range of Flieger and Lagasse's results. It would thus appear that practice had the effect of increasing the

relationship between movement time and the percent acceleration time.

Out of the 18 temporal and quantitative integrated electromyographic pattern parameters seven were specifically related to the biceps brachii activity, eight to the triceps brachii activity, and three are related to the activity of both muscles (latencies and ratio). When examining more closely the correlations associated with the seven biceps brachii parameters in both movement times vectors, two coefficients (for the biceps brachii slope, Q4, and the time to peak activity, T8) were found to increase, none were found to decrease, and five were found to be practically unchanged (for the motor time, T1, duration, T4, silent period, T12, first burst peak activity, Q1, and second burst peak activity, Q2) from the day 1 to the day 3 vector. For the triceps brachii parameters, however, five coefficients (for the motor time, T2, duration, T5, latency to the acceleration-deceleration point, T11, peak amplitude, Q3, and slope, Q5) increased, two decreased (for the time to peak activity, T9, and latency to the point of maximum acceleration, T10), and only one remained unchanged (the cocontraction period motor time, T3) from the day 1 to the day 3 vector. In other words, 71% (or 5 out of 7) of the biceps brachii parameters correlation coefficients were found not to be affected by

practice, whereas, 64% (or 5 out of 8) of the triceps brachii parameters correlation coefficients were found to increase with practice. These results are indicative of an increasing role of the triceps brachii muscle with practice in the control of the maximum speed elbow flexion movement.

Finally, the tension output parameters correlation coefficients with movement time were found to be relatively high. Significant negative correlation coefficients were found in both movement time vectors for all four tension output parameters. These results are somewhat surprising and in disagreement with results reported by Lagasse (1975, 1979) and others (Henry, 1960; Henry and Whitley, 1960). Lagasse, for instance, reported correlation coefficients of -0.29 and -0.01 between movement and maximum isometric flexion and extension strength respectively. In a horizontal arm swing movement, Nelson and Jourdan (1969) reported that a significant correlation ($r = 0.50 - 0.75$) existed between maximum speed of movement and agonist muscle strength. The results of the present study are then more in agreement with the results presented by Nelson and Jordan (1969) than the results reported by Lagasse (1975). However, these results could be due to the presence of both male and female subjects in the sample studied, which increased the range of the scores. In Lagasse's study only male subjects were involved.

Intercorrelation submatrices. The most prominent feature of the two first intercorrelation submatrices (the kinematic parameters and the temporal integrated electromyographic pattern parameters submatrices) is the independent nature of the parameters, as revealed by relatively low correlation coefficients. Furthermore, in general the intercorrelation structure did not seem to be affected by practice to any great extent.

As could be expected, some quantitative integrated electromyographic pattern parameters and all the tension output parameters exhibited relatively high intercorrelation coefficients. The tension output parameter intercorrelation coefficients were also shown to increase slightly from day 1 to day 3. For the quantitative parameters, the correlation between the peak activity and the slope parameters for both the biceps and triceps brachii muscles were found to be high ($r = 0.74 - 0.87$). Because of the nature and definition of these parameters the high correlation coefficients assessed were to be expected.

Multiple regression

The purpose of this last section is to present the results of multiple linear regression analyses attempting to predict movement time from selected parameters, and also to test for the

effect of practice upon performance predictability. In all regression equations presented below movement time, the performance criterion, was taken as the dependent variable, whereas, all the other parameters were utilized as the independent variables.

Due to the nature of the quantification technique utilized, the definition of the parameters and the large number of parameters, several combinations of independent variables were tested. The selection of given independent variables were realized by systematically removing and allowing given parameters in the prediction equation. Hence, not all parameters were entered simultaneously in the regression process. The reason why not all parameters were allowed at once is that due to the quantification technique, movement time can be defined as linear combinations of other parameters. Movement time (K1) can be defined mathematically in this quantification model as follows:

$$K1 = (K2 + T2) - T11, \text{ or}$$

$$K1 = K5 + T10 + T2, \text{ or}$$

$$K1 = (T6 + T2) - T1.$$

Therefore, in order to avoid singular matrices to be involved in the regression process, some set of parameters must be avoided.

Table 76 presents the results of the multiple linear regression analyses when specific parameters were systematically removed. The first parameters to be removed were the triceps brachii motor time (T2) and the time of positive acceleration (K2). The first part of table 76 presents the results of the regression analyses performed of this set of parameters for day 1 and day 3 of the performance stabilization period. For the day 1 data, three independent variables were retained (biceps brachii time to peak activity, T8, percent acceleration time, K3, and triceps brachii burst peak activity, Q3) and 68% of the movement time total variance was accounted for by this prediction equation. The prediction equation for the day 3 data, however, was totally different. Four parameters were kept in the equation: normal flexion tension output (TO1), maximum displacement (K4), biceps brachii first burst to the triceps brachii burst latency (T6), and the triceps brachii burst duration (T5). This last prediction equation accounted for 83% of the movement times total variance. Therefore, from day 1 to day 3 not only was the prediction equation modified but the level of prediction also increased (from 68% to 83%).

The results of the regression analyses when the percent acceleration time (K3) and the triceps brachii burst motor time (T2) were removed are presented in part 2 of table 76. Here

TABLE 76

Prediction equations for the performance criterion, movement time, assessed on the first (DAY 1) and last (DAY 3) days of the performance stabilization period, when parameters were systematically removed. PARM: parameters in equations. b: prediction equation coefficients. R and R^2: multiple correlation coefficient, simple and squared. S.E.: standard error of estimate. INT: intercept.

DAY 1					DAY 3				
PARM	b	R	R^2	S.E.	PARM	b	R	R^2	S.E.
Part 1: Triceps brachii motor time (T2) and time of positive acceleration (K2) removed.									
T8	0.422	0.698	0.488	21.843	T01	-0.477	0.723	0.522	15.042
K3	-1.109	0.790	0.624	18.986	K4	-1.002	0.840	0.706	11.978
Q3	-10.260	0.825	0.680	17.786	T6	0.352	0.871	0.759	11.018
INT	169.691				T5	0.179	0.910	0.828	9.464
					INT	203.389			
Part 2: Percent acceleration time (K3) and triceps brachii motor time (T2) removed.									
K2	0.644	0.756	0.572	19.966	T01	-0.479	0.723	0.522	15.042
T04	0.828	0.825	0.680	17.508	K4	-1.027	0.840	0.706	11.978
Q4	-0.279	0.855	0.730	16.331	T1	0.338	0.879	0.772	10.712
K4	-0.706	0.871	0.759	15.681	T9	0.138	0.890	0.791	10.408
K5	0.303	0.891	0.794	14.740	T04	-0.274	0.894	0.799	10.399
INT	169.192				INT	246.524			
Part 3: Kinematic parameters, biceps to triceps brachii latency (T6) and triceps brachii to maximum acceleration latency (T10) removed.									
T9	0.250	0.698	0.488	21.843	T01	-0.497	0.723	0.522	15.042
T03	-0.711	0.782	0.611	19.321	T2	0.528	0.868	0.754	10.960
T2	0.311	0.845	0.714	16.833	T9	0.271	0.897	0.805	9.914
T1	0.590	0.867	0.751	15.946	T3	-0.329	0.919	0.845	8.964
INT	70.148				INT	95.223			

again, the prediction equations differed drastically from day 1 to day 3, and the level of prediction increased slightly (from 79.4% to 79.9%). In this case, five parameters composed both prediction equations. The day 1 equation was formed of the parameters time of positive acceleration (K2), fast extension tension output (TO4), biceps brachii first burst slope (Q4), maximum displacement (K4), and time to maximum acceleration (K5). The day 3 prediction equation was composed of the following five parameters: normal flexion tension output (TO1), maximum displacement (K4), biceps brachii burst motor time (T1), triceps brachii time to peak activity (T9), and fast extension tension output (TO4).

In the third and last part of table 76, the kinematic parameters along with the biceps brachii to triceps brachii bursts latency (T6) and the triceps brachii burst to the point of maximum acceleration latency (T10) were removed. The resulting day 1 prediction equation included the following four independent variables: triceps brachii burst time to peak activity (T9), normal extension tension output (TO3), triceps brachii burst motor time (T2), and the biceps brachii first burst motor time (T1). The day 3 prediction equation was composed of the four parameters that follows: normal flexion tension output (TO1), triceps brachii burst motor time (T2), triceps brachii burst time to peak activity (T9), and triceps brachii cocontraction period

motor time (T3). As for all previous prediction equations, the level of prediction (R^2) increased from day 1 to day 3 (from 75% to 85%). Another important factor that must be observed, common to all three parts of table 76, is the important reduction in the standard error of estimate of the prediction equation (S.E.) from day 1 to day 3. It appeared that practice had the effect of increasing performance prediction possibilities. This increase in predictability was also accompanied by a modification in the parameter contributions to the prediction equation. Lagasse (1975) reported that 77% to 81% of the variance associated with the maximum speed of movement could be accounted for by a combination of neuromuscular coordination control mechanisms. In the present study, 80% to 85% of that variance could be accounted for in practiced subjects. Lagasse (1975) also reported that the percent acceleration time was responsible for 56% to 64% of the movement time total variance, whereas, the sequential muscle activation was responsible for 37% to 47% of the total variance, and that muscle strength accounted for only 2% to 13% of the movement time total variance. The present study was not able to duplicate these results. For instance, in the day 3 data the flexion tension output was found to be one of the best predictor of the maximum speed of movement, which alone accounted for 52% of its total variance.

Finally, table 77 presents the results of linear multiple

TABLE 77

Prediction equations for the performance criterion, movement time assessed on the first (DAY 1) and last (DAY 3) days of the performance stabilization period, when parameters were systematically added. PARM: parameters in equations. b: prediction equation coefficients. R and R^2: multiple correlation coefficient, simple and suared. S.E.: standard error of estimate. INT: intercept.

DAY 1					DAY 3				
PARM	b	R	R^2	S.E.	PARM	b	R	R^2	S.E.
Part 1: Kinematic parameters only.									
K2	1.264	0.756	0.572	19.962	K3	-1.759	0.599	0.359	17.418
K3	-1.927	0.990	0.980	4.335	K2	1.230	0.994	0.989	2.351
INT	154.575				INT	144.846			
Part 2: Biceps brachii parameters only.									
T1	1.328	0.591	0.394	24.608	T1	0.555	0.583	0.340	17.683
T4	0.425	0.700	0.491	22.104	Q4	-0.305	0.651	0.424	16.764
INT	-6.203				T8	0.228	0.672	0.452	16.611
					INT	95.420			
Part 3: Triceps brachii parameters only.									
T9	0.533	0.698	0.487	21.843	T2	0.425	0.694	0.482	15.662
T2	0.498	0.781	0.610	19.335	T9	0.369	0.811	0.658	12.909
T5	-0.226	0.808	0.653	18.538	Q3	-17.553	0.838	0.701	12.255
INT	43.189				Q5	0.536	0.854	0.729	11.871
					INT	57.816			

regression analyses when only specific subsets of parameters were allowed in the regression process. In the first part of table 77, only the kinematic parameters were allowed in the equations. In both the day 1 and day 3 data the only two parameters to be included in the prediction equations were the time of positive acceleration (K2) and the percent acceleration time (K3). In both cases the prediction of movement time was near perfect. However, when only biceps brachii related integrated electromyographic pattern parameters were allowed in the prediction equations the results indicated that the level of prediction was low (table 77, part 2). Only two biceps brachii parameters (first burst motor time, T1, and duration, T4) were included in the day 1 prediction equation that accounted for only 49% of the movement time total variance. The day 3 equation included the three following parameters which accounted for only 45% of the movement variance: first burst motor time (T1), slope (Q4) and time to peak activity (T8). In the third part of table 77 are presented the results of multiple linear regression analyses when only triceps brachii parameters were allowed in the equations. In both day 1 and day 3 prediction equations the two first parameters to be included were the triceps brachii motor time (T2) and time to peak activity (T9). In the day 1 prediction equation only the total duration (T5) was added to reach a level of prediction of 65%. In the day 3 prediction equation, however, both the peak activity (Q3) and slope (Q5)

were added to the equation that reached a R^2 of 73%. Therefore, the prediction equations differed slightly from day 1 to day 3 and the level of prediction also increased, while the standard error of estimate of the prediction equations decreased markedly from day 1 (S.E. = 18.538) to day 3 (S.E. = 11,871). Hence, as reported by Lagasse (1975) the acceleration time seems to be playing an important role in maximum speed of movement prediction. Even more significant, the present results indicate that triceps brachii related parameters played a more important role than the biceps brachii related parameters in the prediction of movement time, which role increased with practice.

DISCUSSION

Reliability

The reliability analysis realized in this study served many purposes. The obvious one was to test for the reproducibility of the criterion measures over days and over trials. A second purpose was to verify if during the performance stabilization period practice effects were monitored. The third purpose of this analysis was to assess the stability and consistency of the quantification technique developed for this study, and finally, the fourth and last purpose was to test for the reliability of the stimulation parameters utilized by the functional electrical stimulation model in order to individualize the stimulation treatments.

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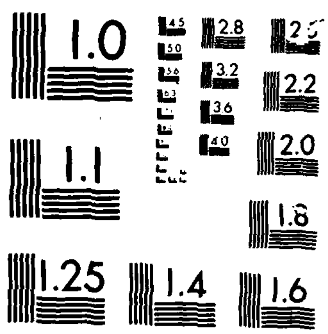

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Movement Parameters

As presented above, the movement parameters include the following:

-Kinematic parameters; movement time (K1), time of positive acceleration (K2), percent acceleration time (K3), maximum displacement (K4), and time to maximum acceleration (K5).

-Temporal integrated electromyographic pattern parameters; biceps brachii first burst motor time (T1), triceps brachii burst motor time (T2), triceps brachii cocontraction period motor time (T3), biceps brachii first burst duration (T4), triceps brachii burst duration (T5), biceps brachii first burst to triceps brachii burst latency (T6), biceps brachii first burst to triceps brachii cocontraction period latency (T7), biceps brachii first burst time to peak activity (T8), triceps brachii burst time to peak activity (T9), triceps brachii burst to the point of maximum acceleration latency (T10), triceps brachii burst to the specific acceleration-deceleration point of inflexion latency (T11), and the biceps brachii silent period (T12).

-Quantitative integrated electromyographic pattern parameters; biceps brachii first burst peak activity (Q1), biceps

brachii second burst peak activity (Q2), triceps brachii burst peak activity (Q3), slope of the biceps brachii first burst (Q4), slope of the triceps brachii burst (Q5), and integrated electromyographic ratio (Q6).

-Tension output parameters; normal (TO1) and fast (TO2) flexion isometric maximum voluntary tension output, and normal (TO3) and fast (TO4) extension isometric maximum voluntary tension output.

The intraclass reliability coefficient and the variance estimates for all these parameters were presented in table 42 and the results were presented above. All parameters, including the performance criterion (movement time), were assessed to be very reliable. The high reliability of kinematic, electromyographic and strength parameters did not come as a surprise. The reliability of such parameters monitored during the execution of maximum speed human movement has been demonstrated several times (Boucher, 1980; Boucher and Flieger, 1983; Flieger, 1983; Lagasse, 1975, 1979; Lagasse and Hayes, 1973; Wolcott, 1977). However, this study introduced several novel parameters, and all the parameters were quantified according and original integrated electromyography quantification technique developed for this study. Therefore, verifying the reliability of these parameters served also to validate the quantification technique utilized.

The results obtained herein were not only shown to be reliable but they were also shown to be in the range of similar parameters assessed in previous studies during identical experimental movements (Flieger, 1983; Lagasse, 1975, 1979). Hence, this technique appeared to be an efficient and rapid way of quantifying kinematic and integrated electromyographic parameters.

Furthermore, by demonstrating the reliability of the parameters it insures that modifications which occurred in these parameters during the treatment period was due to treatment effects and not random error or lack of reliability.

Performance Stabilization

The performance stabilization period was designed to allow practice effects to take place and, thus, allow the maximum speed forearm flexion movement performance to stabilize. The practice taking place during this period (i.e., 15 repetitions / day) was shown to be responsible for a significant decrease in movement time. As expected, the subjects became faster with practice. This modification in the movement performance was accompanied by modifications occurring in other parameters. Noticeably, the time of positive acceleration, the burst durations, and the integrated electromyographic ratio, are all parameters that

decreased from the first to the last practice day. Such decreases, even if not statistically significant, represent an increase in the efficiency of the muscle contractions and their coordination, which occurred with practice. Therefore, when the subjects were subjected to the different experimental treatments during the treatment period, motor learning, as demonstrated by the gain in movement efficiency, had already taken place. As planned, therefore, the purpose of the functional electrical stimulation treatments administered during the treatment period was not one of strict motor learning but rather one of motor performance manipulation. The improvement in movement performance and contraction efficiency insured that a given level of motor learning had been achieved by the subjects. The role of the functional electrical stimulation was then of further modification of the movement performance and not simply one of modifying a novice state of movement performance.

Stimulation Parameters

Several stimulation parameters were monitored and used to determine the stimulation pattern administered to the subjects. The rheobase, single pulse duration and stimulus intensity for both the biceps and triceps brachii muscles were the six stimulation parameters monitored before every stimulation

session. Both the rheobase and the stimulus intensity for both the biceps and triceps brachii muscles were shown to be very stable across days and very consistent. The intraclass reliability coefficient for these four parameters ranged from 0.86 to 0.94. Therefore, both the rheobase and stimulus intensity appeared to be reliable parameters to utilize in the functional electrical stimulation model in order to individualize the stimulation patterns. The single pulse duration, as defined above, for both the biceps and triceps brachii muscles exhibited relatively high day variance and a very low true score variance. In fact, all the subjects stimulated were shown to be very homogeneous for this parameter. Therefore, the resulting intraclass reliability coefficients were very low (0.18 for the biceps brachii muscle and 0.39 for the triceps brachii muscle). Hence, this parameter was deemed too unreliable to utilize in the functional electrical stimulation model. Single pulse duration should have been seen as useful in the determination of the pulse frequency, the frequency being defined as the inverse of the duration. In this study however, the frequency was considered as a constant at either 50 Hz or a 1 kHz. It is probably a good thing that the frequency was defined as a constant since this parameter was not reliable. This last parameter being so unreliable, would have yielded unreliable pulse frequencies and, thus, the effect of frequency could not have been controled. The effect of pulse frequency was then assessed in this study by

fixing it at two given values (50 Hz and 1 kHz).

Summary

All the movement parameters, and thus the quantification technique developed for this study, were found to be very reliable (R = 0.49 - 0.92). The high reliability and stability of these parameters is in accord with several previous studies (Boucher, 1980; Lagasse, 1975,1979; Wolsott, 1977). Furthermore, the practice that took place during the performance stabilization period was shown to elicit the expected modification in the maximum speed forearm flexion movement performance and pattern. Finally, four of the six stimulation parameters were shown to be very reliable. The single pulse duration for both the biceps and triceps brachii were shown to be unreliable (R = 0.18 and 0.39 respectively). However the two parameters were not utilized in the determination of the stimulation pattern. Only the rheobase and stimulus intensity, which were reliable, were utilized for establishing the stimulation pattern.

Experimental Treatment Effects

This section was designed to assess the effects of functional electrical stimulation upon stabilized human

performance and the underlying neuromuscular coordination control mechanisms. The effects of pulse frequency and stimulation modality (progression and retrogression) upon the functional electrical stimulation treatment efficiency were also assessed.

The data discussed herein were collected during the treatment period. The results of the analyses of variance performed on these data was, therefore, also interpreted.

Movement parameters

The 27 movement parameters monitored for this study were divided into three groups: kinematic, integrated electromyographic and tension output parameters. The kinematic parameters yielded information concerning the level of performance achieved during the execution of the experimental movement. The integrated electromyographic parameters represented an indirect assessment of the contribution of different neuromuscular coordination control mechanisms in the production of the experimental movement. Finally, the tension output parameters allowed the verification of the treatment effects upon the mechanisms underlying the production of maximum voluntary isometric contractions.

Kinematic parameters. The maximum speed forearm flexion movement performance was shown to be significantly modified from the first to the last treatment period day (table 70). As expected, the performance modification was measured to be a decrease in movement time (table 43), the performance criterion. Thus, it was observed that maximum speed human performance could be modified by experimental treatment even following a three-day performance stabilization period. In the kinematic parameters, however, the group or treatment main effect was never found to be statistically significant (tables 71 and 72). Therefore, the enhanced performance was found to be over all groups. As presented below, even if not statistically significant, some noticeable group differences were observed.

The decreased movement time, which is representative of an improvement in the maximum speed forearm flexion movement performance, is in accord with most of the functional electrical stimulation litterature (Boucher 1980; Fleury and Lagasse, 1979; Lagasse et al., 1979; Liberson et al., 1961; Vodovnik, 1971a). In all the previously cited works functional electrical stimulation was utilized for two specific purposes: (1) movement and neuromuscular retraining in rehabilitation, to allow disabled patients to recover normal movements (Liberson et al., 1961; Merletti et al., 1978; Stanic et al., 1977; Vodovnik et al., 1965; Voodovnik, 1971a, 1971b); and (2) motor learning from a

novice state (Boucher, 1980; Lagasse et al., 1979) The present functional electrical stimulation study was original in that treatments were administered following performance stabilization, and that the functional electrical stimulation patterns were individualized following a model developed for this study. Therefore, the present results demonstrate that functional electrical stimulation, as well as traditional practice, can influence performance even following three practice or performance stabilization days. The way in which the underlying machanisms were affected is discussed immediatly below.

Integrated electromyographic parameters. The results of the temporal and quantitative integrated electromyographic pattern parameters analyses of variance were presented above (tables 72 and 73). Out of these 18 parameters nine presented statistically significant day and/or day-group effects. Even more interesting, is that all of these nine parameters are associated with the antagonist muscle or the end of the movement. Therefore, it appeared that mechanisms underlying antagonist muscle contractions were more affected by the experimental treatments than the mechanisms controlling the agonist muscle.

For example, the day main effect (D) and day-group interaction (DG) were shown to be statistically significant for

the biceps brachii second burst peak activity (Q2) and the slope of the triceps brachii burst (Q5) as can be seen on table 73. In order to illustrate the modifications occurring in these parameters during the treatment period, figures 11 and 12 present the relative day changes with every group. Figures 11 and 12 present the modification occurring across days by transforming the absolute day means into a percent of the initial day 1 mean. This presentation procedure was utilized in order to present all the groups with a common initial day 1 value (100%), which allows a day-group comparison free of initial value discrepancies. As can be seen in both these figures, the treatment administered greatly influenced the day means modification pattern for both these parameters. For both these parameters the passive control group (1) had very little effect, whereas the practice control group (2) increased these parameters from day 1 to day 2 and decreased from day 2 to day 3. Since further traditional practice effects were observed in the treatment period, it can be thought that both these parameters might not have been stabilized by the end of the performance stabilization period.

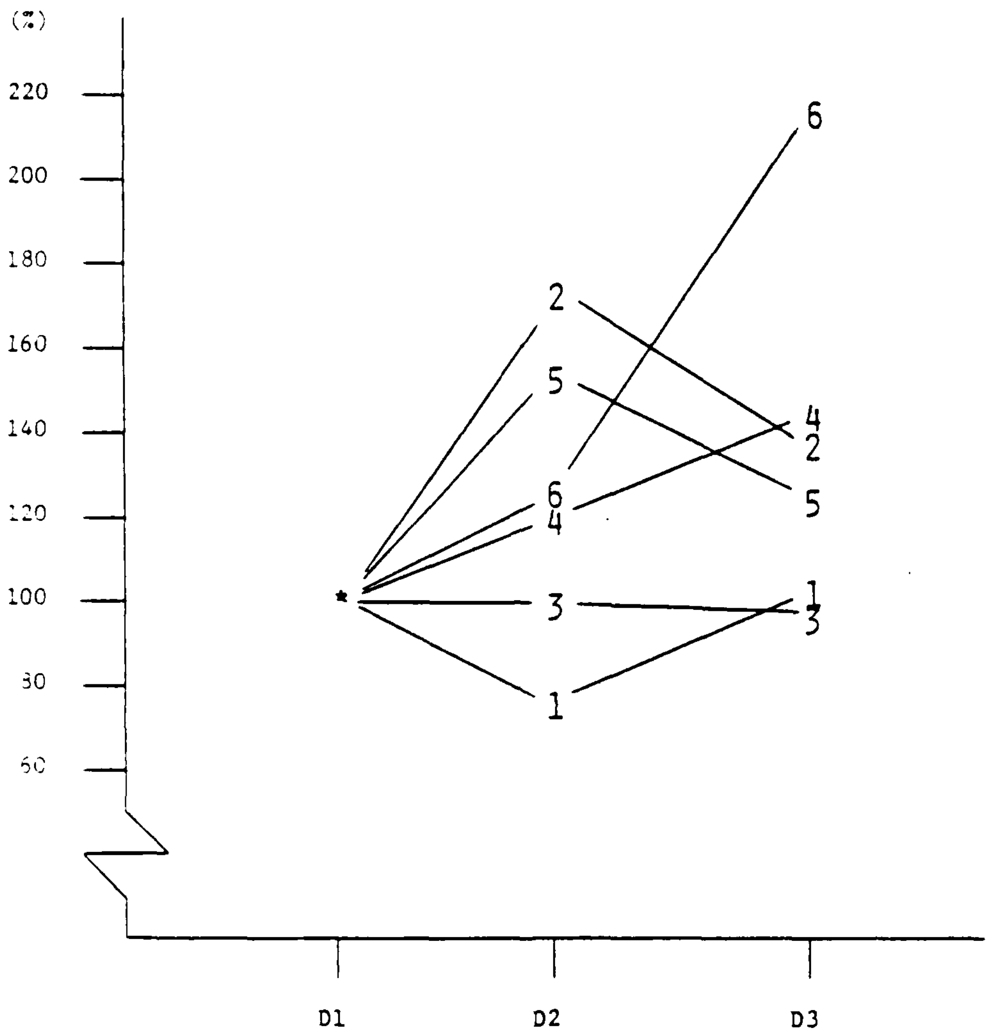

Figure 11. Relative day modifications occurring over all treatments for the biceps brachii second integrated electromyographic burst peak activity during the experimental treatment period.D1, D2 and D3: Testing days. Groups: Passive (1) and practice (2) controls, high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6). *: 100% common initial level.

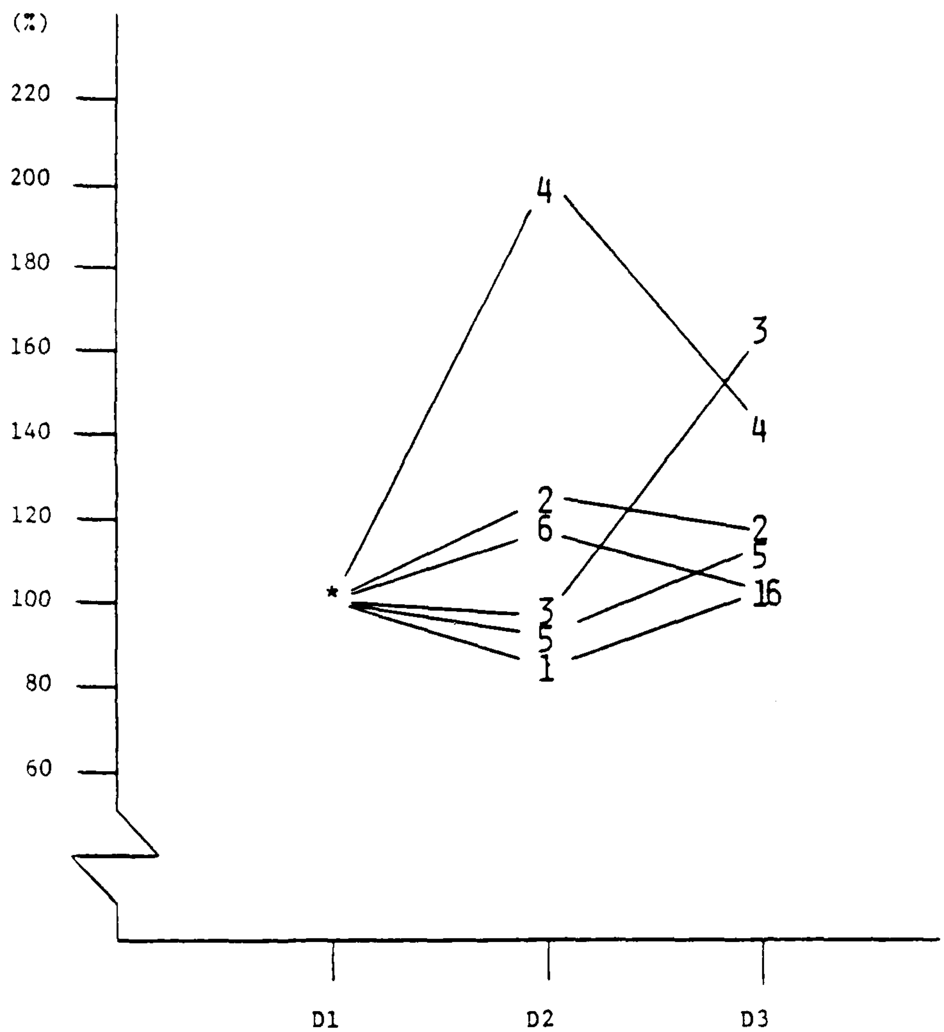

Figure 12. Relative day modifications occurring over all treatments for the slope of the triceps brachii integrated electromyographic burst during the experimental treatment period. D1, D2 and D3: Testing days. Groups: Passive (1) and practice (2) controls, high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6). *: 100% common initial level.

Also in both figures 11 and 12, another feature is noticeable, that is, the progression functional electrical stimulation groups (3 and 5), presented similar day means modification patterns which were the opposite of the retrogression functional electrical stimulation group (4 and 6) pattern. Therefore, the pulse frequency seemed to have very little differential effects, whereas, the modality of functional electrical stimulation was responsible for the significant day-group interaction in both these parameters. This is especially true when comparing the high frequency progression (3) and retrogression (4)groups for the slope of the triceps brachii burst parameter (Figure 12). This phenomenon will be further discussed below.

As stated above, the nine parameters that exhibited statistically significant day and/or day-group effects were all associated with the antagonist muscle or the end of the movement. Different underlying mechanisms were thus affected differently during the treatment period. Furhtermore, the agonist muscle and its latency with respect to the antagonist muscle were not affected by the experimental treatment while the antagonist muscle actions were greatly modified in the same period. The decrease in movement time measured during the treatment period

was then accompanied by a modification in the antagonist muscle actions mostly. More specifically, the slope of the antagonist muscle burst seemed to have played a major role, along with the agonist muscle second burst amplitude. Since the integrated electromyographic slope parameter is an indirect measurement of the motor unit recruitment pattern, it appeared that the treatment effects upon the antagonist muscle were in two folds: (1) modifications in the temporal components (i.e., decreased duration) and (2) modification in the motor unit recruitment pattern. For the retrogression groups (4 and 6) the slope of the triceps brachii burst increased from day 1 to day 2 and decreased from day 2 to day 3 (Figure 12). For the progression groups (3 and 5) the slope of the triceps brachii parameter was unaffected from day 1 to day 2 and increased from day 2 to day 3. For the same groups, the effects of the high frequency groups (3 and 4) appeared more acute than the effects of the low frequency groups (5 and 6). Therefore, the effect of functional electrical stimulation upon the antagonist muscle motor unit recruitment pattern occurred following a highly complex process. The modification of this neuromuscular coordination control mechanism is probably due to the interaction of phenomena, of which the agonist to antagonist latency and intensity ratio are important.

Finally, both the temporal and quantitative components of the antagonist muscle activity were affected by the experimental

treatments, while the agonist muscle first burst was not affected. The decrease in movement time occurring during the treatment period could be explained by a decrease in the antagonist muscle motor time. When the antagonist muscle motor time is shortened, as in this study, it means that the onset of agonist muscle activity is getting closer to the end of the movement. Therefore, the agonist muscle first burst propulsive action is left unimpaired and the speed of movement is increased. These results can be due to the modification of a preprogram responsible for the execution of the maximum speed forearm flexion movement. These modifications have most probably resulted from sensory imparted learning effects elicited by the functional electrical stimulation treatments. Such an hypothesis is in accord with the reverse loop theory proposed by Kroll et al. (1983).

<u>Tension output parameters</u>. The treatment effects upon tension output parameters were considered of secondary importance in this study. Due to the relatively low stimulus intensity utilized during the functional electrical stimulation treatments (Tables 32 and 35) no substantial treatment effects were expected. However, the fast flexion tension output parameter was found to have been modified significantly across days, and the day-group interaction (DG) was also found to be statistically

significant (Table 74). Interestingly, the only tension output parameter to have been affected during the treatment period represents the exact type of force generation utilized during the execution of the maximum speed forearm flexion movement (i.e., explosive agonist muscle contraction). Therefore, the modifications occurring in this parameter may have been the result of a better coordination of the agonist and antagonist muscles during the production of fast maximum voluntary isometric contraction. Such inprovement in coordination may have occurred as a result of a transfer of learning from the maximum speed forearm flexion task to the fast maximum voluntary isometric contraction. These two tasks being so similar, especially in their preparation and onset phases, maybe the motor program responsible for the production of fast flexion tension output was modified in the same fashion as the preprogram responsible for the execution of the maximum speed forearm flexion movement.

Pulse frequency and stimulation modalities

As mentioned above, the pulse frequencies (50Hz and 1kHz) and the stimulation modalities (progression and retrogression) influenced differently the functional electrical stimulation treatment efficiency (Figure 9 and 10). For the performance criterion, movement time (K1), only the day main effect (D) was found to be significant (Table 70). However, when the relative

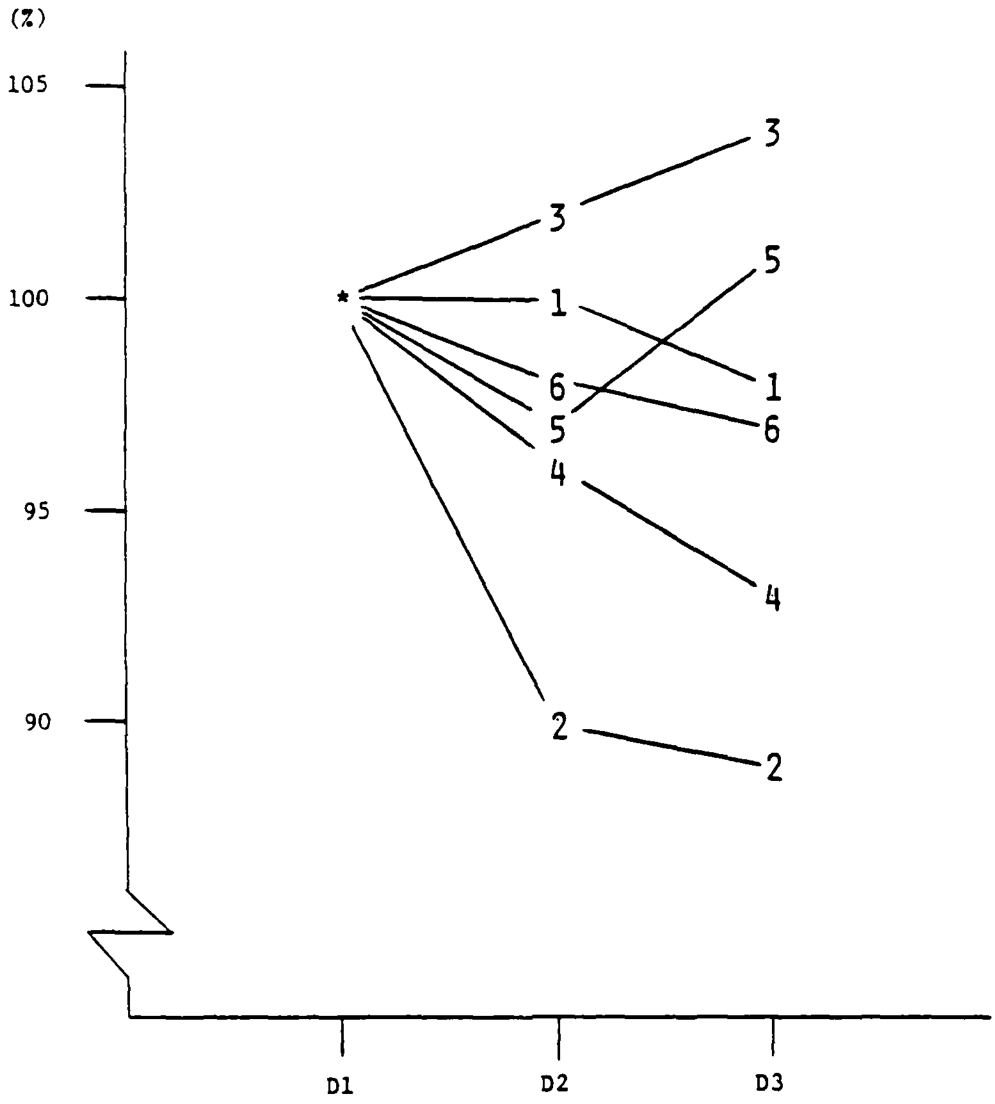

Figure 13. Relative day modifications occurring over all treatments for the movement time during the experimental treatment period. D1, D2 and D3: Testing days. Groups: Passive (1) and practice (2) controls, high frequency progression (3) and retrogression (4), and low frequency progression (5) and retrogression (6). *: 100% common initial level.

changes across days are plotted for every group, several noticeable patterns emerged (Figure 13). As could be expected, the passive control group (1) did not undergo a noticeable modification from the first to the last treatment period days. However, the movement time for the practice control group (2) decreased by 10% from the first to the second day, whereas, it leveled off between days 2 and 3. This sharp initial decrease in movement time may indicate that the performance was not completely stabilized after the three-day performance stabilization period.

The feature that should be highlighted on figure 13 is the effect of the functional electrical stimulation modalities. It is remarkable that the two progression groups (3 and 5) exhibited similar day mean pattern, which was opposite the pattern present in the retrogression groups (4 and 6), and that was regardless of the pulse frequency. The movement time tendency was to increase in the progression groups and to decrease in the retrogression groups (Figure 13). In the progression groups both the inter-muscle latency and the intensity ratio were increased. The rationale was that by increasing the latency between the onset of the two muscles, the agonist muscle could accelerate the limb more freely for a longer period of time and, thus, increase the movement velocity and reduce movement time. However, even if this logic seemed good one important factor was overlooked. With

movement improvement, movement time was shown to decrease significantly. This decrease in movement time can be attributed to an enhanced muscle contraction efficiency and to a better coordination between agonist and antagonist muscles. The better coordination between muscles is reflected as a reduction in the amount of cocontraction occurring during the execution of the movement. However, the reduction in cocontraction is not necessarily due to an absolute increase in the inter-muscle latency. The reduction in cocontraction is due to a complex interaction of several neuromuscular coordination control mechanisms. The duration of the agonist muscle propulsive burst is reduced while its motor time remains unaffected, and the antagonist muscle burst motor time is reduced, all that occurring in a much shorter movement time. Therefore, the absolute value of the latency can in fact decrease even though the level of cocontraction decreases, which conclusion can help explain the results presented on figure 13 (i.e., decreasing movement time for a decreased latency in groups 4 and 6). The results obtained during the treatment period was then opposite to the basic functional electrical stimulation model assumption. It remains, however, that by manipulating the latency through modelled functional electrical stimulation, the maximum speed forearm flexion movement performance was modified in a consistent maner. Supprisingly, manipulating the pulse frequency did not seem to have any drastic effects. Therefore, muscular contractions

obtained from the stimulations might be more important than the way in which specific motor unit pools are activated. These results are consistent with Vodovnik's model (1971a) which proposes that the functional electrical stimulation effects are mediated mostly through the responses of the muscle spindles. The spindles are known to respond to muscle loading and unloading or to fast modifications in the extrafusal muscle fibers length. Hence, regardless of the pulse frequency, when a muscle is stimulated it shortens quickly, thus, activating the muscle spindles through the muscle spindle unloading reflex no matter what pulse frequency is utilized.

Lastly, the lack of functional electrical stimulation efficiency with increased inter-muscle latency is consistent with Boucher's (1980) findings. Boucher reported that when the stimulation latency was increased by 20 ms (15%) the effect of the functional electrical stimulation treatment was comparable to the control group. However, when the latency remained shorter the effects of the functional electrical stimulation treatment were as great as for traditional practice. Hence, by increasing the latency the treatment efficiency was reduced. In the present study similar results were found. The progression groups modality turned out to be less efficient than the retrogression groups modality. These results are thus in accord with Boucher's previous findings and, hence, not so supprising.

Summary

As expected the functional electrical stimulation treatments were responsible for a modification in movement time. It was observed that the modification in movement time was due to modifications occurring in antagonist muscle related parameters such as the duration and slope of the integrated electromyographic burst. The agonist muscle propulsive first burst was unaffected during the treatment period. It appeared, then, that the agonist and antagonist muscles studied were not controlled by the same set of neuromuscular coordination control mechanisms. The reduction in movement time may have been the result of modifications of a preprogram through the modelled functional electrical stimulation sensory imparted learning effects. These preprogram modifications responsible for reducing the movement occurred in the antagonist muscle mostly, and they were in two folds: (1) temporal modifications, and (2) motor unit recruitment pattern modifications. These results tend to demonstrate that the enhanced performance following its stabilization is mostly due to the modification of underlying neuromuscular coordination control mechanisms, and not to the agonist and antagonist muscles length-tension characteristics as proposed by Engelhorn (1983) among others (Bizzi, Polit and

Morasso, 1976; Cook, 1979: Polit and Bizzi; 1979).

Finally, the maximum speed forearm flexion movement performance was manipulated differently by different modelled functional electrical stimulation modalities, whereas, the pulse frequency did not seem to influence the treatment effeciency. The progression modality had the effect of increasing movement time, while the retrogression treatment had the reverse effect.

Performance Predictability

This last section served several purposes. First, by studying the correlation structure of all the parameters monitored, some redundancies in the information collected were assessed. Then by attempting to predict movement time from the parameters measured, the relative importance of individual parameters was established. Lastly, by comparing the prediction equations found for the performance stabilization period day 1 and day 3 data, the effect of practice upon the performance predictability was evaluated.

Parameter redundancy

The computerized technique utilized to quantify most of the parameters studied was developed specially for this study. The

utilization of this technique allowed the quantification of several original parameters. The reliability of the parameters was presented above and was in general very good. However, due to the originality of several parameters, and the lack of supporting data, some parameters could be redundant or having the same information content. The redundancy of the parameters was then established by studying the intercorrelation structure found in the 27 parameters measured in this study.

The intercorrelation matrix was presented in table 75. In the kinematic parameters submatrix, for both the upper (day 1 data) and lower (day 3 data) diagonals, the Pearson correlation coefficients were relatively low. Suprisingly, the relation between the time of positive acceleration (K2) and the percent acceleration time (K3) was very low ($r = 0.27 - 0.31$). Because the percent acceleration time is the time of positive acceleration expressed as a percent of movement time, one could have expected that these two parameters would be highly correlated. However, the common variance expressed by these two parameters was very low. Therefore, they represent two different types of information, and contrary to what might have been expected these parameters are not redundant.

Similarly, in the temporal integrated electromyographic pattern parameters submatrix no subset of highly correlated

parameters was found. Thus, these 12 parameters must represent somewhat independent portions of the information that can be recorded during a maximum speed forearm flexion movement. For the quantitative integrated electromyographic pattern parameters, for both the upper and lower diagonals (day 1 and day 3 data) two parameters were found to be somewhat redundant: The peak activity and the slope. For both the agonist muscle first burst and the antagonist muscle burst these two parameters were highly correlated (r = 0.74 - 0.87). Both the parameters represent a measurement of the quantity of activity generated by the muscle during the execution of the movement. Because the parameters were measured for integrated electromyography, they both represent the summation of individual myoelectric potentials. It was, therefore, not surprising to find a high correlation between these parameters, and in future integrated electromyographic studies it may be recommended to measure only one of these parameters.

Finaly, the tension output parameters submatrix presented highly redundant parameters. The correlations between normal and fast tension output were found to be very high (r = 0.96 - 0.98). Both these parameters represent a measurement of maximum isometric strength even though the contraction modalities are different. Hence, it would be justified to measure only one type of contraction, either slow or fast, or to combine all

measurements for analysis purposes.

Day effect

Tables 76 and 77 present several movement time prediction equations. Table 76 presents three sets of equations where specific parameters were systematically removed in order to avoid singular design matrices in the multiple regression process. Table 77 also present three sets of equations where, this time, specific group of variables were allowed in the equations.

In all three sets of equations of table 76, the prediction possibilities of the equations, as given by R and R^2, increased from the day 1 to the day 3 data. Furthermore, the standard error of estimate also decreased, and the independent variables composing the equations were different from one day to the other. For example, in the day 1 data when the time of positive acceleration (K2) was removed the percent acceleration time (K3) was included (table 76 part 1) and vice-versa (table 76 part 2). However, in the day 3 data in the two first parts of table 76, the maximum displacement was the only kinematic parameter to be included in the prediction equations. As mentioned above, the adequacy of the prediction equation fit was always much better for the day 3 data. Even in the second part of table 76 where

R^2 was almost unchanged from day 1 to day 3 (R^2 = 0.794 and 0.799), the standard error of estimate dropped significantly (S.E. = 14.740 and 10.399). Thus, practice had for effect not only of increasing the prediction capabilities but also to modify the independent variables inter-relationships. Hence, the present results demonstrate that performance is more readily predictable after practice. Threfore, when interpreting the results of studies dealing with movement performance predictability, one should be aware of the effect of practice, and the total number of practice trials should always be reported.

Finally, table 77 presents the contribution of specific groups of variables along with the day or practice effects. The first part of table 77 presents the prediction equations when only the kinematic parameters were allowed in the regression process. Only the time of positive acceleration (K2) and the percent acceleration time (K3) were included in both the day 1 and day 3 prediction equations. As mentioned above, these two parameters are independent and thus represent two types of information concerning the acceleration pattern of the maximum speed forearm flexion movement. Lagasse (1975) reported that percent acceleration time alone was responsible for up to 64% of the total movement time variance. In this study, up to 99% of the movement performance criterion was accounted for when both

the percent and raw (time of positive acceleration) acceleration times were measured and fitted in the equations. According to the Newtonian physics, acceleration is the second derivative of displacement. Therefore, in a system where all variables are controlled, displacement and thus movement time can be perfectly calculated from the acceleration signal. Similarly, by describing the acceleration pattern more completly by measuring both the percent and raw acceleration times, performance or movement time can be predicted almost perfectly. These results are therefore consistent with the physics laws linking acceleration to displacement.

Finally, parts 2 and 3 of table 77 present the prediction equations when only the biceps brachii parameters and only the triceps brachii parameters were allowed in the prediction equations. In part 2, when only the biceps brachii parameters were allowed in the equations, is the only case where the predictability decreased with practice ($R^2 = 0.49$ for day 1 and 0.45 for day 3). Therefore, not only was the biceps brachii parameters contribution to the prediction of performance very low (less than 50%) but it also decreased with practice. The exact opposite was found for the triceps brachii parameters (table 77 part 3). In this last case, the level of prediction was fair and it increased with practice ($R^2 = 0.65$ for day 1 and 0.73 for day 3). In both day 1 and day 3 prediction equations, the

triceps brachii motor time and time to peak activity were found to be important predictors of performance. The major difference between the pre- and post-practice prediction equations was in the last independent variables included. For the pre-practice (day 1 data) prediction equation the triceps brachii burst duration was added, whereas, the triceps brachii slope and peak activity were included in the post-practice (day 3 data) prediction equation. Therefore, the antagonist muscle motor unit recruitment pattern seems to play a more important role in post-practice performance prediction. When comparing the results found in the two last parts of table 77, the antagonist muscle activity appeared to be a better predictor of movement performance. In both novice and practiced subject the object was to execute the forearm flexion movement as fast as possible. Therefore, in both novice and practiced subjects the movement strategy should be of contracting the agonist muscles as forcefully as possible. What would then make the difference between novice and practiced subjects is how the movement is stopped on target. Hence, the antagonist muscle activity was a better predictor of the maximum speed forearm flexion movement performance.

Summary

By studying the intercorrelation structure, several

parameters appeared to be redundant, or representing the same movement information. In that respect, the slope and peak activity for both muscles, and the fast and normal tension output for both muscles were found to be highly correlated and, hence, deemed to be redundant parameters.

Finally, human performance predictability appeared to be affected by practice. Practice was found to increase the level of performance predictability that could be achieved by the parameters studied. Furthermore, the time of positive acceleration and percent acceleration time were found to be the best predictors of movement performance. Lastly, the antagonist muscle activity was shown to play a major role in performance predictability, and was more important than the agonist muscle activity. The antagonist muscle was then seen as playing a major role in the motor learning process of the maximum speed forearm flexion movement.

SUMMARY

Historically, the utilization of electrical stimulation in the treatment of disease goes back to the great Roman and Greek Empires era. In 46 A.D., Roman and Greek physicians utilized the electrical discharge of torpedo fishes in the treatment of pain associated with headache, gout and hemorrhoids. Today, electrical stimulation is not only widely accepted and utilized but it has become a field in its own right. More recently, a newer electrical stimulation technique, functional electrical stimulation, has come to the center of attention.

Functional electrical stimulation takes its roots in the now classical work of Liberson et al. (1961). In their original work, Liberson et al. applied this technique to the correction of the foot drop in seven hemiplegic patients. Following electrical stimulation, Liberson et al. found that the patients could

dorsiflex the affected foot by themselves. These results were responsible for the onset of an explosion of the research on the effects of functional electrical stimulation. Since 1961 up to very recently, functional electrical stimulation was mostly being used in the treatment of patients suffering from arthritis, post-operative orthopedic problems, spinal cord injury, and stroke. It had been accepted that functional electrical stimulation can be responsible for muscle rehabilitation and movement reeducation. More recently, a series of studies investigating the motor learning effects of functional electrical stimulation was realized. According to the information available to date, it would appear that functional electrical stimulation represents a promissing technique to induce motor learning by altering the neuromuscular coordination control mechanisms that underlie human movement. It would appear that a novel motor task can be learned without having to practice or execute that given motor task. However, in all the functional electrical stimulationresearch works to date, all subjects were stimulated according to the same pattern of muscle activation. All subjects were stimulated according to an averaged functional electrical stimulation pattern originating from practiced "donors". Therefore, the functional electrical stimulation effects could be optimized by adapting the stimulation pattern to every individual subject. In that respect, the goal of the present study was to examine the feasibility of neuromuscular coordination control

mechanisms manipulation through modelled functional electrical stimulation.

This study proposed principally to address the two following questions: (1) what are the effects of the funtional electrical stimulation treatments upon the neuromuscular coordination control mechanisms; (2) what are the effects of different functional electrical stimulation treatment conditions.

Methodology

Thirty-six subjects randomly allocated into two control groups (passive and traditional practice control groups) and four functional electrical stimulation groups (high frequency progression, high frequency retrogression, low frequency progression, and low frequency retrogression, functional electrical stimulation groups) reported to the Motor Integration Laboratory for three pre-test and two post-test days. The pre-test days, administered before the experimental treatment periods, were at most 48 hours apart, whereas, the last pre-test and the two post-test days were interspersed with two weeks of experimental treatment. All testing days were designed to assess experimental parameters for the execution of the experimental movement; a class B maximum speed forearm flexion movement

executed through the sagittal plane with the forearm in a semiprone position. A specially designed apparatus was utilized in order to standardize the execution of the maximum speed forearm flexion movement and monitor kinematic, integrated electromyographic and tension output informations. From the collected informations the following parameters were derived:

-Kinematic parameters; movement time, time of positive acceleration, percent acceleration time, maximum displacement, and time to maximum acceleration.

-Temporal integrated electromyographic pattern parameters; biceps brachii first integrated electromyographic burst motor time, triceps brachii integrated electromyographic burst motor time, triceps brachii cocontraction period motor time, biceps brachii first integrated electromyographic burst duration, triceps brachii integrated electromyographic burst duration, biceps brachii to triceps brachii integrated electromyographic latency, biceps brachii to triceps brachii cocontraction period integrated electromyographic latency, biceps brachii first integrated electromyographic burst time to peak integrated electromyographic activity, triceps brachii integrated electromyographic burst time to peak integrated electromyographic activity, triceps brachii integrated electromyographic burst to the point of maximum

acceleration latency, triceps brachii integrated electromyographic burst to the specific acceleration-deceleration point of inflexion latency, biceps brachii integrated electromyographic silent period.

-Quantitative integrated electromyographic pattern parameters; biceps brachii first integrated electromyographic burst peak activity, biceps brachii second integrated electromyographic burst peak activity, triceps brachii integrated electromyographic burst peak activity, slope of the biceps brachii first integrated electromyographic burst, slope of the triceps brachii integrated electromyographic burst, integrated electromyographic ratio.

-Tension output parameters; flexor and extensor normal and fast maximal isometric tension output.

The pre-test days were designed to allow performance stabilization of the maximum speed forearm flexion movement and the post-test days to assess the possible treatment effects. The treatment effects studied included a control situation (no treatment), a traditional practice and four different functional electrical stimulation treatments. The functional electrical stimulation treatments were a progression and a retrogression treatment both under a high and a low pulse frequency conditions.

Following data collection, reduction and quantification, reliability of all experimental parameters were assessed by an intraclass correlation analysis of variance. The treatment, days and trials, main effects were assessed using a split-split-plot analysis of variance design. The predictability of the performance criterion, movement time, by the experimental parameters were ascertained using a forward and backward stepwise linear multiple regression model.

Results

The results of this study were divided into three sections: (1) reliability, assessed on the performance stabilization period data; (2) treatment effects, assessed on the treatment period data; and (3) performance predictability, assessed on the data of the first and last day of the performance stabilization period. The results obtained under all three precited sections can be summarized as follows:

1. All the kinematic parameters, the temporal and quantitative integrated electromyographic pattern parameters, and tension output parameters were found to be reliable (R = 0.49 -

0.97). In general, the magnitude of the intraclass reliability coefficient was closely related to the magnitude of the true score variance estimate. Furthermore, all parameters monitored were found to be more consistent across days than across trials.

2. For the stimulation parameters, both the rheobase and the stimulus intensity for both the biceps and triceps brachii muscles were found to be highly reliable (R = 0.87 - 0.93). However, the single pulse duration for both muscles was found not to be reliable (R = 0.18 - 0.39). The low intraclass reliability coefficients for this last stimulation parameter was due to the very low true score variance estimates (TRUE = 2.17 - 2.73), as compared to the trial and day variance estimates.

3. Movement time was found to increase with practice during the performance stabilization period. Furthermore, movement time was also found to decrease significantly from the first to the last treatment period day. The different treatments were shown to influence movement time differently. Noticeably, though not statistically significant, the progression functional electrical stimulation treatments, regardless of the pulse frequencies, had the effect of increasing movement time, whereas, the retrogression

treatments resulted in a decreased movement time. Hence, pulse frequency did not appear to be a crutial variable in the functional electrical stimulation treatment efficiency, whereas, the different modalities tested (progression an retrogression) affected the performance criterion differently.

4. Of all the temporal and quantitative integrated electromyographic pattern parameters measured (18 parameters), only nine parameters exhibited a statistically significant difference for the day main effect. Remarkably, of these nine parameters eight were m. triceps brachii related parameters. Thus, the activation pattern of the antagonist muscle was affected by the different experimental treatment more so than the activity of the agonist muscle.

5. Supprisingly, even if the stimulation intesity was relatively low, the fast flexion tension output was significantly affected during the treatment period. Both the day main effect and the day-group interaction were found to reach a statistically significant level for this parameter. These modifications assessed in fast flexion tension output may have been due to the modifications that occurred in the neuromuscular coordination control mechanisms underlying the maximum speed forearm flexion

movement. This would help explain why only the fast flexion tension output was affected by the stimulation.

6. Performance predictability appeared to be drastically influenced by performance stabilization. In all prediction equations fitted, the multiple regression coefficient increased from the first to the last day of the performance stabilization data, and the standard error of prediction decreased. Movement time was almost perfectly predicted by the time of positive acceleration and the percent acceleration time. When these kinematic parameters were not allowed in the equation, triceps brachii parameters appeared to play an important role in movement time prediction. Furhtermore, the level of prediction achieved by the triceps brachii parameters increased with practice, whereas, the role of biceps brachii parameters decreased with practice. Hence, it appeared that with practice the level of performance was more readily predicted by the way in which the movement was stopped on target, and not the way the forearm was propulsed.

Recommendations

This study was realized in four folds: (1) development of

the integrated electromyographic quantification technique, (2) assessement of the performance stabilization effects and reliability of the parameters, (3) evaluation of the experimental treatment effects including all modalities of functional electrical stimulation, and (4) assessement of the practice effects upon movement performance predictability. Thus, several different recommendations were enunciated.

All experimental parameters monitored were found to be reliable. Hence, the computarized technique developed herein appeared to be most efficient. Computerized quantification allowed a more complete assessement of the electromyographic events occurring during ballistic movements. Furhtermore, it allowed a rapid quantification of large amount of data. However, in order to have a more complete understanding of the neuromuscular mechanisms underlying maximum speed of movement, it would be recommended to assess raw electromyographic parameters such as spike amplitude and frequency along with integrated electromyographic pattern parameters.

Regarding the experimental treatments, modelled functional electrical stimulation appeared to be an efficient technique in order to manipulate movement performance. Therefore, such technique could see many usefull applications in the rehabilitation and reeducation of movements in handicaped

patients such as in hemiplegia. However, the temporal inter-muscle latency might not have been the optimal control parameter. Their must exist a more efficient way to measure the level of coordination between agonist and antagonist muscles. A new movement parameter should take into consideration the decreasing movement time, decreasing cocontraction and increasing muscle contraction efficiency with practice. For example, such a parameter could be a measurement of latency as a percent of movement time. Therefore, the field of modelled functional electrical stimulation is a relitively new field in which further investigation is needed.

Finally, practice was shown to influence drastically performance predictability. Practice was also found responsible for several neuromuscular coordination control mechanism modifications. Thus, the exact number of practice trials and practice regimens should always be clearly reported when presenting data concerning the prediction of movement performance or data concerning neuromuscular coordination control mechanisms underlying human movements.

Conclusions

Based upon the results of the present study, and within its

limitations, the following conclusions are appropriate:

1. Modelled functional electrical stimulation, following human performance stabilization, is an efficient technique to induce alterations in human performance by manipulating the neuromuscular coordination control mechanisms underlying maximum speed of human movement.

2. Human performance stabilization, through traditional practice, is responsible for reducing movement time by modifying the neuromuscular coordination mechanisms underlying maximum speed of human movement.

3. The temporal and quantitative integrated electromyographic parameters are reliable measurements of neuromuscular coordination control mechanisms underlying maximum speed of human movement.

4. the flexion and extension normal and fast isometric voluntary contraction tension output represent very reliable parameters.

5. The rheobase is a reliable stimulation parameter essential to modelled functional electrical stimulation.

6. The single pulse duration is not a reliable stimulation parameter.

7. Following human performance stabilization, human performance can be manipulated in both a progression and a retrogression direction through modelled functional electrical stimulation.

8. Pulse frequency has very little effect upon modelled functional electrical stimulation treatment efficiency.

9. Specific modelled functional electrical stimulation modalities induce alterations in human performance and the neuromuscular coordination control mechanisms similar to the traditional practice alterations.

10. The no treatment control situation does not inflence human performance and the neuromuscular coordination control mechanisms underlying maximum speed of human movement.

11. Human performance predictability is drastically modified by human performance stabilization through traditional practice.

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APPENDIX B

SAMPLE SIZE ESTIMATION ANALYSIS

Sample Size Estimation Analysis

Treatment effects sample size estimation

Movement time mean = 150 ms

Movement time effect size (10%) = 15 ms

Movement time standard deviation = 13 ms

Intraclass R = 0.88

Confidence level = 0.05

Power = 80%

$$d' = {}^{\text{effect size}}/_{\text{standard deviation}}$$

$$d' = {}^{15}/_{13} = 1.15$$

$$d = {}^{d'}/_{\sqrt{1-R}}$$

$$d = {}^{1.15}/_{\sqrt{1-0.88}} = 3.32$$

Therefore, according to the sample size tables (Cohen, 1969, p. 53) for a power of 80%, a confidence level of 0.05 and d=3.32;

Sample Size Estimation = 6 subjects per group.

Treatment condition effects sample size estimation

Movement time mean = 150 ms

Movement time effect size (10%) = 15 ms

Movement time standard deviation = 13 ms

Confidence level = 0.05

Power = 80%

$$d = {}^{\text{effect size}}/_{\text{standard deviation}}$$

$$d = {}^{15}/_{13} = 1.15$$

Therefore, according to the sample size tables (Cohen, 1969, p. 53) for a power of 80%, a confidence level of 0.05 and d=1.15;

Sample Size Estimation = 12 subjects per group.

However, for a power of 50% the sample size is reduced to:

Sample Size Estimation = 6 subjects per group.

APPENDIX C

FUNCTIONAL ELECTRICAL STIMULATION MODEL

Functional Electrical Stimulation Model

All functional electrical stimulation pattern parameters will be derived from the integrated electromyography pattern parameters according to the following model.

Pulse duration determination voltage

The pulse duration determination voltage is the intensity at which the stimulator will be set in order to determine the pulse duration for a given muscle, and it is defined as follows:

$$V_{PD} = (\Delta \times K_I) + R$$

where Δ = delta = 2;

V_{PD} = pulse duration determination voltage;

R = rheobase;

K_I = intensity constant.

Delta (Δ) was fixed at 2 because this value represents the smallest increment or division for the intensity setting of the Grass S-88 stimulator. K_I, for the biceps brachii, takes the value of the integrated electromyography ratio, whereas, for the triceps brachii $K_I = 1$.

Stimulation intensity

The stimulation intensity is the voltage at which the stimulator is set for a given muscle during the actual treatment session and it is defined as follows:

$$V_{STIM} = V_{PD} \pm (K_L \times V_{PD}) + K_{STIM}$$

where V_{STIM} = stimulating intensity;

V_{PD} = pulse duration determination voltage;

K_L = learning constant or coefficient (0.1 or 10%);

K_{STIM} = stimulation voltage constant (10 volts).

The learning constant or effect size investigated will be established at 10%. The + or - refers to the specific functional

electrical stimulation groups, progression (+) or retrogression (-).

Pulse frequency

The effects of a high and a low pulse frequency will be investigated in this study. The low pulse frequency will be set at 50 hertz and the high pulse frequency at 1000 hertz.

Train duration

The train duration for a specific muscle will be set equal to its respective integrated electromyography burst duration.

Stimulation latency

The functional electrical stimulation pattern biceps brachii to triceps brachii latency will be derived from the biceps brachii to triceps brachii integrated electromyography latency in the following manner:

$$L_{STIM} = L_{IEMG} \pm (K_L \times L_{IEMG})$$

where L_{STIM} = functional electrical stimulation pattern biceps brachii to triceps brachii latency;

L_{IEMG} = biceps brachii to triceps brachii integrated electromyography latency;

K_L = learning constant or coefficient (0.1 or 10%).

As for the stimulation intensity, the + or - will be selected according to the specific functional electrical stimulation group, progression (+) or retrogression (-).

APPENDIX D

SAMPLE SIZE ADEQUACY ANALYSIS

Sample Size Adequacy Analysis

Treatment effects sample size adequacy

MSdays = 2494.36

MSerror = 579.90

k = number of days = 3

n = number of elements = 180

DF1 = k-1 = 2

DF2 = n-k = 177

Confidence Level = 0.05

$$\phi = \frac{\sqrt{\frac{k-1}{n} \cdot (MS_{days} - MS_{error})}}{\sqrt{MS_{error}} \;/\; \sqrt{n}}$$

$$= \frac{\frac{2}{180} \cdot (1914.46)}{24.08 / \sqrt{180}} = \frac{4.62}{1.80}$$

$$= 2.57$$

Therefore, according to the power tables (Kirk, 1968), the power for a confidence level of 0.05 and the degrees of freedom of 2/177 was found to be of 98%.

Treatment condition effects sample size adequacy

MSgroups = 11516.11

MSerror = 7810.11

k = number of groups = 6

n = number of elements = 90

DF1 = k-1 = 5

DF2 = n-k = 84

Confidence Level = 0.05

$$\emptyset = \frac{\sqrt{\frac{k-1}{n} \cdot (MS_{groups} - MS_{error})}}{\sqrt{MS_{error}} \; / \; \sqrt{n}}$$

$$= \frac{\sqrt{\frac{5}{90} \cdot (3706.00)}}{88.37 \; / \; \sqrt{90}} = \frac{14.35}{9.32}$$

$$= 1.54$$

Therefore, according to the power tables (Kirk, 1968), the power for a confidence level of 0.05 and degrees of freedom of 5/84 was found to be of 65%.

APPENDIX C

High Frequency Electrical Stimulation of Agonist and Antagonist Muscle Groups Involved in Fast Forearm Movement: Effects Upon Movement Time and the Triphasic EMG Pattern

INTRODUCTION

Low frequency electrical stimulation has been used for the treatment and strengthening of disused muscles by therapists for several decades. Dr. Yakov Kots, a Russian investigator, has claimed that electrical stimulation, employing a very high frequency of 2,500 Hz, can produce isometric contractions of 10-30% greater force than normal. Because of the stronger contractions he reported that highly trained athletes increased their levels of strength by 30-40 percent in 20 sessions consisting of 10 contractions of 10 seconds duration, with a 50 second rest interval. Until recently no Russian type stimulator was available and the effectiveness of the technique could not be substantiated. However, Micromed Instruments in Canada now manufactures the Electrostim 180 which produces stimulus trains of 2500 cycles per second.

In 1983 Currie and Mann used 4 groups of subjects to study the effectiveness of the high frequency electrical stimulation on the knee extensor muscles. The groups consisted of: 1) a control group, 2) a group that performed only isometric exercise, 3) a group that received electrical stimulation and 4) a group that did both isometric exercise and received electrical stimulation. The intensity of the electrical stimulation was set for at least 60% of each individual's pretest strength values. Analysis showed that each of the experimental groups differed significantly from the control group with the group that performed only the exercise achieving the greatest increase in torque gain. The group that received only electrical stimulation also significantly increased the torque output of the involved muscles.

Since the therapeutic benefits of electrical stimulation would be many if the technique proved to be as successful as that described by

Kots, it is necessary to attempt to substantiate his claims.

METHODOLOGY AND STRENGTH RESULTS

Measurements

Ten male and ten female college aged students participated in this investigation. The subjects were placed in two groups with 5 men and 5 women in each group. One group received electrical stimulation of the biceps brachii and the other group received stimulation of the triceps brachii. Each subject reported to the laboratory for four pre-test days and two post-test days. During each session the following measurements were procured:

1. Fifteen trials of ballistic forearm flexion speed of movement on the flexors of one arm and the extensors of the contralateral arm and 15 trials of the same parameter with a load equal to 7 times the natural moment of inertia of the limb.

2. Two slow and two fast maximum voluntary isometric contractions of the flexors of one arm and the extensors of the contralateral arm.

3. Endurance holding times of the flexors of one arm and the extensors of the contralateral arm with a load equal to 50% of the maximum voluntary isometric strength.

Testing Procedure

A piece of apparatus was specifically designed to assess forearm flexion and forearm extension speed of movement. The subject was seated on a stool adjusted for height in a way that allowed the upper arm to be situated parallel to the floor. The subject was positioned so that the chest was placed against a padded chest rest and a strap was placed around the back and attached to the apparatus to minimize extraneous

movement. The forearm was attached to a wooden bar 50 cms. in length via a leather cuff placed around the wrist. The placement of the cuff on the bar was determined by having the subject place the center of rotation of the elbow joint at the axis of the wooden bar. This axis consisted of oil bearings and was connected to a potentiometer to measure angular displacement. For the measurement of forearm flexion movement speed, the distal end of the wooden bar rested on a microswitch that was mounted on a wooden pedestal which was positioned 15 degrees from horizontal. On the verbal command, "Ready-Go", the subject was instructed to lift the wooden bar and bring it through 15 degrees as fast as possible and to volitionally stop it at a foam target placed at 90 degrees from horizontal. Initiation of movement triggered a microswitch which started a millisecond starter (Lafayette Instruments Corporation, model 54419). The clock was stopped by a second microswitch when the bar reached its 90 degree position.

For forearm extension, the subject began with the arm at the 90 degree position. Upon leaving this position the microswitch was activated and the subject again executed 75 degrees of movement. A second microswitch was triggered by means of a stiff spring placed across a microswitch. The flexibility of the spring forced the subject to volitionally stop the movement while not hindering the execution of the action. Again a foam target was placed at the level of the microswitch to indicate to the subject where movement should be stopped. It should be noted that for both flexion and extension, if the subject overshot the target by 15 degrees or more a buzzer sounded. When this occurred, a mistrial was declared and the trial was repeated.

Using Beckman couplers (model 9852) and amplifiers, the electromyographic activity of the biceps brachii and triceps brachii muscles was amplified, integrated, and recorded on a Beckman (type R) Dynagraph recorder. Following data collection, a computer program was used to analyze the data on a Nova-3 minicomputer (Data General Corporation) interfaced with a sonic sensory screen and a Graf pen (model GP3, Science Accessories Corporation) for the digitizing of electromyographic patterns. In addition movement time was measured by a millisecond timer (Lafayette Instrument Co., model 54419). Movement time was measured from initiation of movement, which triggered a microswitch, to the time when a second microswitch is triggered at the 90 degree target. A potentiometer contained in a control box, and attached to the proximal end of the wooden bar via a common axle measured limb displacement during the movement.

To measure maximum voluntary isometric strength of the forearm flexors and extensors, a leather cuff on the subject's wrist was attached directly to a strain gauge. The strain gauge was positioned to the apparatus so that the arm was pulling at a 90 degree angle to the strain gauge. The flexion strength was measured with the forearm at a 90° angle to the strain gauge. For measurement of extension strength, the forearm was at a 90 degree angle from horizontal and attached to a strain gauge via a specially designed apparatus which holds the strain gauge horizontal. The arm pulled on the strain gauge at a 90 degree angle.

For the measurement of a slow voluntary isometric contraction, the investigator gave the commands "Ready-Go". On "Go" the subject progressed to a maximum contraction within three seconds and held it for a brief period. When executing a fast maximum voluntary isometric contraction the subject performed a maximum contraction immediately upon the command "Go".

From the maximum strength trials, 50% of the weight was suspended from a pulley system. The subject was instructed to hold the forearm at a 90 degree position for as long as possible. The amount of time the subject held the weight was recorded with a stop watch.

Following the pre-test measurements each subject reported to the laboratory for 18 sessions of electrical stimulation. During each session 2 carbon rubber electrodes were placed on the belly of the muscle to be stimulated and 10 isometric contractions lasting 15 seconds were administered with 50 seconds of rest between each contraction. Each subject was allowed to adjust the intensity of the contraction themselves by controlling the amount of current from the machine. The average intensity of contraction for the males who had their biceps stimulated was 40.0 milliamps, while those that had their triceps stimulated averaged 40.3 milliamps. The females who had their biceps stimulated received an average of 23.9 milliamps and those that had their triceps stimulated averaged 25.2 milliamps. After the 18 sessions, two post test days allowed measurement of the previously described parameters on the flexors and extensors of each arm.

RESULTS

The strength values for the females are presented in table 1. The females who received stimulation of the biceps brachii showed no increase in strength for either the flexors or extensors of the stimulated arm or for the flexors of the contralateral arm. The extensor strength of the contralateral arm increased 5.7%. Those receiving stimulation of the triceps brachii had no increase in strength in any of the measurements. The males demonstrated a 23% increase in extension strength on the arm

TABLE 1. FEMALE STRENGTH VALUES OF THE FLEXORS AND EXTENSORS OF THE EXPERIMENTAL AND CONTRALATERAL ARM (N=10).

	FLEXORS STIMULATED			
	EXPERIMENTAL ARM		CONTRALATERAL ARM	
MUSCLE GROUP	MEAN	S.D.	MEAN	S.D.
FLEXORS				
PRE-TEST	53.15	9.49	49.82	9.00
POST TEST	53.14	9.55	49.62	11.96
EXTENSORS				
PRE-TEST	29.62	6.65	32.56	7.31
POST TEST	28.72	8.74	34.40	5.57
	EXTENSORS STIMULATED			
FLEXORS	MEAN	S.D.	MEAN	S.D.
PRE-TEST	55.00	6.80	48.94	8.67
POST TEST	55.27	3.19	47.40	8.14
EXTENSORS				
PRE-TEST	31.16	9.80	34.90	11.33
POST TEST	30.30	6.54	34.58	14.92

VALUES ARE IN POUNDS

TABLE 2. MALE STRENGTH VALUES OF THE FLEXORS AND EXTENSORS OF THE EXPERIMENTAL AND CONTRALATERAL ARM (N=10).

	FLEXORS STIMULATED			
	EXPERIMENTAL ARM		CONTRALATERAL ARM	
MUSCLE GROUP	MEAN	S.D.	MEAN	S.D.
FLEXORS				
PRE-TEST	75.49	7.36	70.21	24.29
POST TEST	76.36	10.97	75.94	8.71
EXTENSORS				
PRE-TEST	41.54	8.34	45.22	15.41
POST TEST	51.10	12.39	51.92	6.33
	EXTENSORS STIMULATED			
FLEXORS	MEAN	S.D.	MEAN	S.D.
PRE-TEST	79.08	11.58	76.14	10.66
POST TEST	81.88	3.82	77.43	9.69
EXTENSORS				
PRE-TEST	43.57	10.08	49.73	12.59
POST TEST	48.92	15.84	46.82	7.21

VALUES ARE IN POUNDS

which had the flexors stimulated. On the contralateral non-stimulated arm the flexion strength increased 8.16% and extension strength increased 14.82%. The males who had their extensors stimulated showed a 12.28% increase in extension strength and a 3.54% increase in flexion strength of the stimulated arm. The contralateral arm demonstrated only a 1.70% increase in the flexors. One probable reason for the increase in the extension strength when the flexors were stimulated is that the contraction of the flexors was so rigorous that the triceps brachii was forced to contract vigorously in order to stabilize the joint. That is, without contraction of the triceps brachii the forearm would have actually flexed upward at the elbow joint. In order to prevent the movement, antagonist contraction was required. However, the contraction elicited by the extensors was more restricted by the elbow joint and the co-contraction of the flexors was not required to the same degree. For further investigations it is recommended that the arm be stabilized by experimental means instead of having the subject restrict the movement themselves.

The movement time data (tables 1-8) for pretest one and pretest two show that the times tended to decrease. This, of course, can be attributed to a learning of the skill. However, when post-test measurements were recorded, the movement times in general did not get faster than those during the pretest measures. The exceptions to this include the following:

1. The females who had their extensors stimulated showed an 8.5% faster movement time with their flexion speed for the unloaded condition and a 5.8% faster speed with the loaded condition. The contralateral arm also showed a 3.5% faster flexion movement speed.

2. The females who had their flexors stimulated showed a 7.5% faster movement speed in the contralateral homologous muscle.

3. The males who had their flexors stimulated had 5.3% and 5.5% faster movement times for load 0 and load 3 flexion respectively and 12.4% and 12.9% faster times for their extension speeds.

4. The males who had their extensors stimulated showed a 12.4% faster movement speed in the stimulated muscles.

The main conclusion reached by this investigation is that the high frequency stimulation technique did not increase the level of strength to the levels reported in the literature. As a result of this study the following recommendations for further studies of this kind are as follows:

1. The EMG output of the muscles should be monitored during the stimulation sessions in order to more accurately quantify the intensity of the contraction.

2. The stimulations should be administered using a technique that will restrict movement of the limb rather than requiring the subject to restrict the movement.

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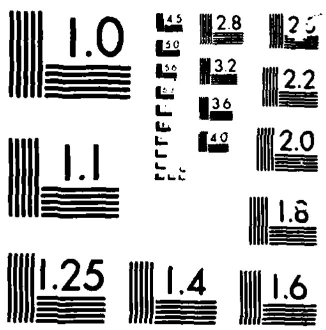

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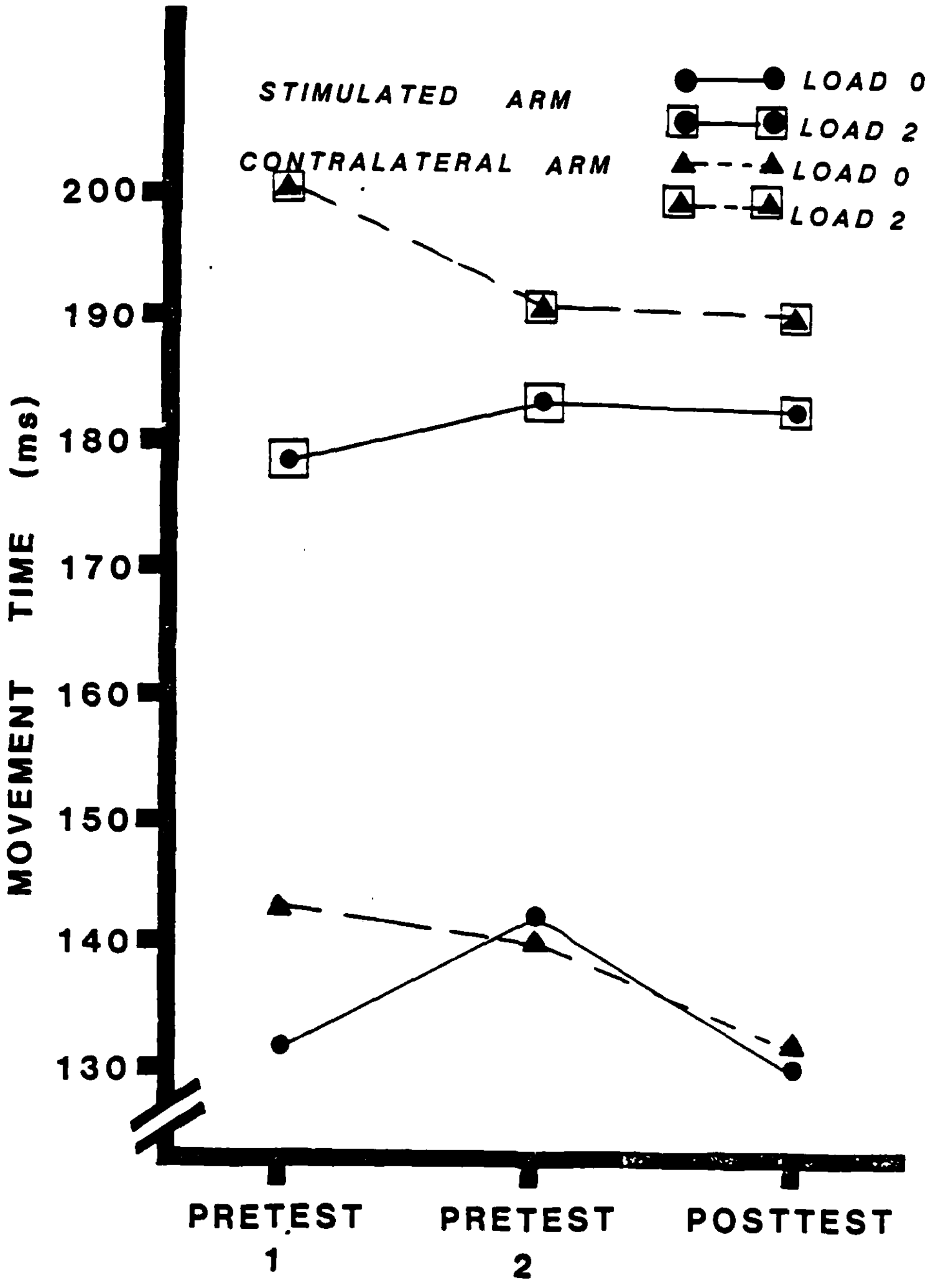

Figure 1. Female movement times for stimulated and contralateral arm flexion. Flexors were the stimulated muscles.

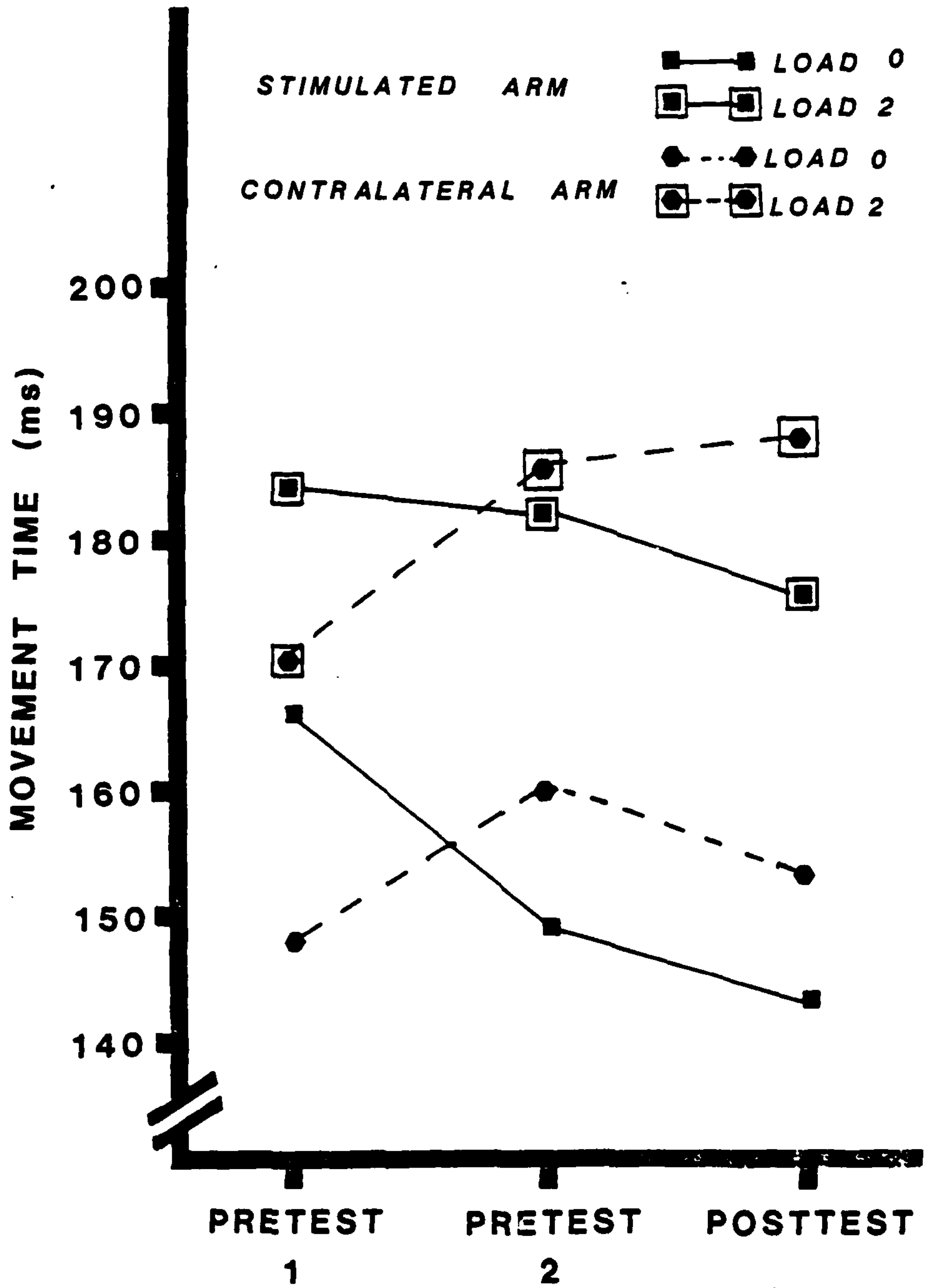

Figure 2. Female movement times for stimulated and contralateral arm extension. Flexors were the stimulated muscles.

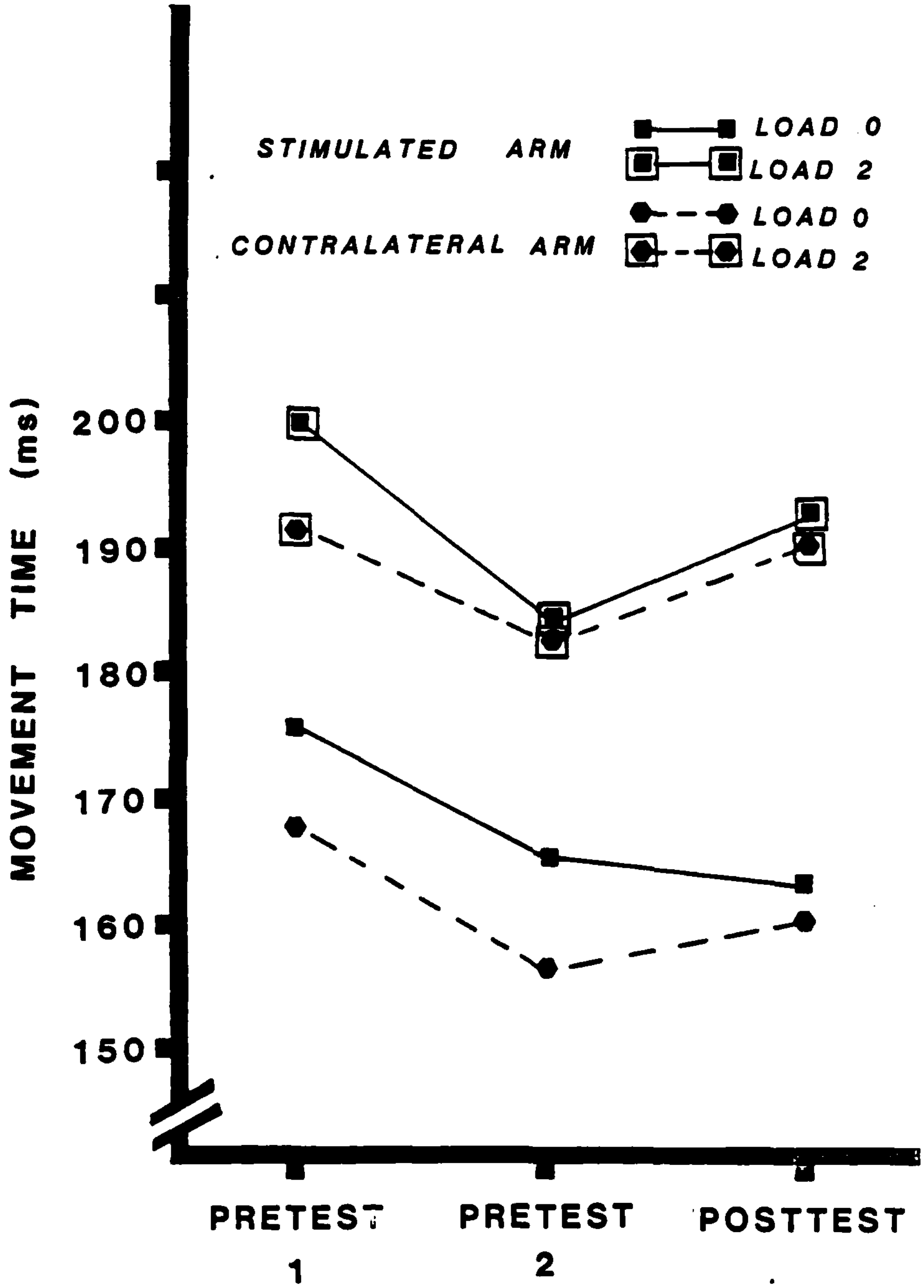

Figure 3. Female movement times for stimulated and contralateral arm extension. Extensors were the stimulated muscles.

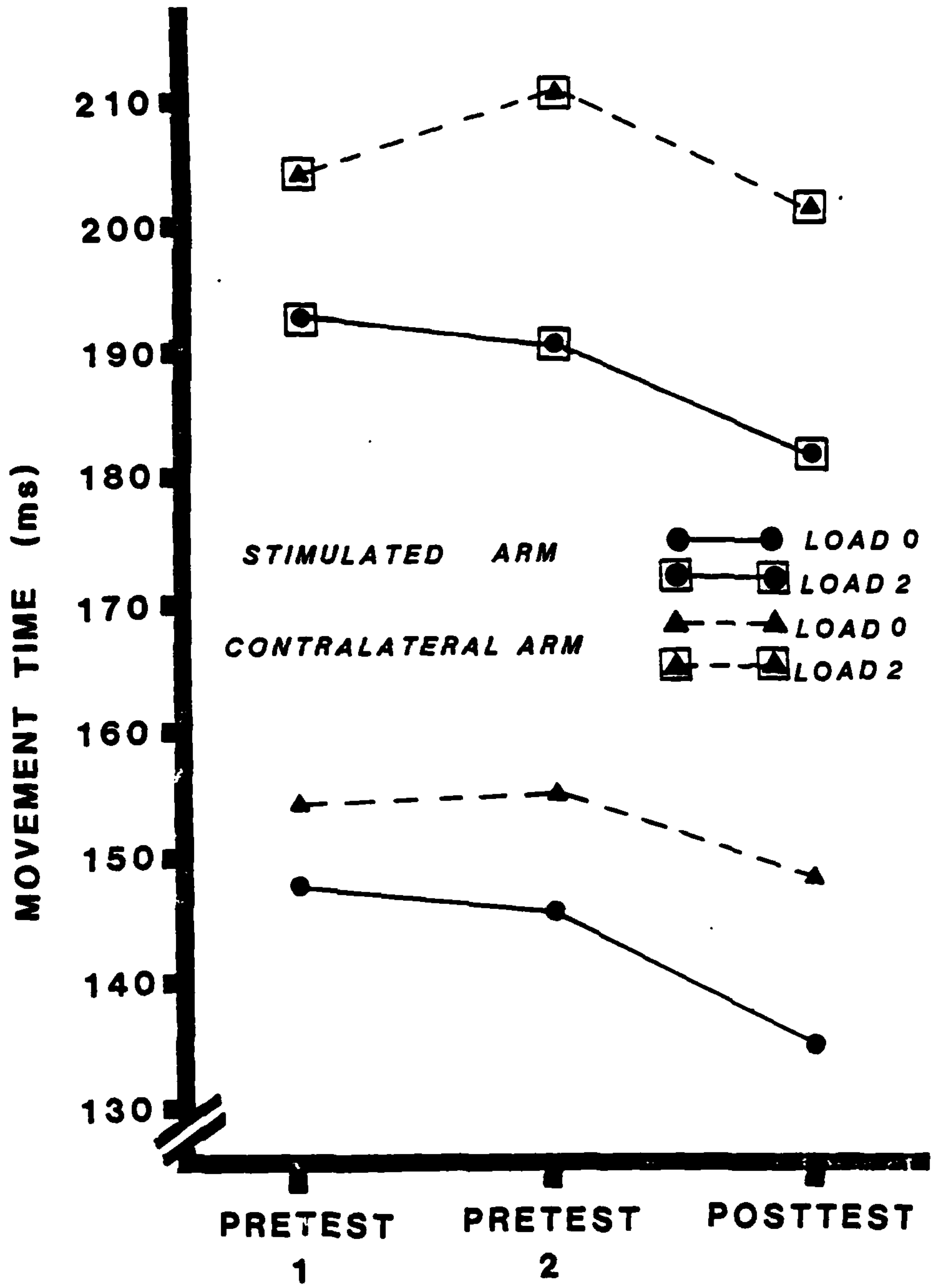

Figure 4. Female movement times for stimulated and contralateral arm flexion. Extensors were the stimulated muscles.

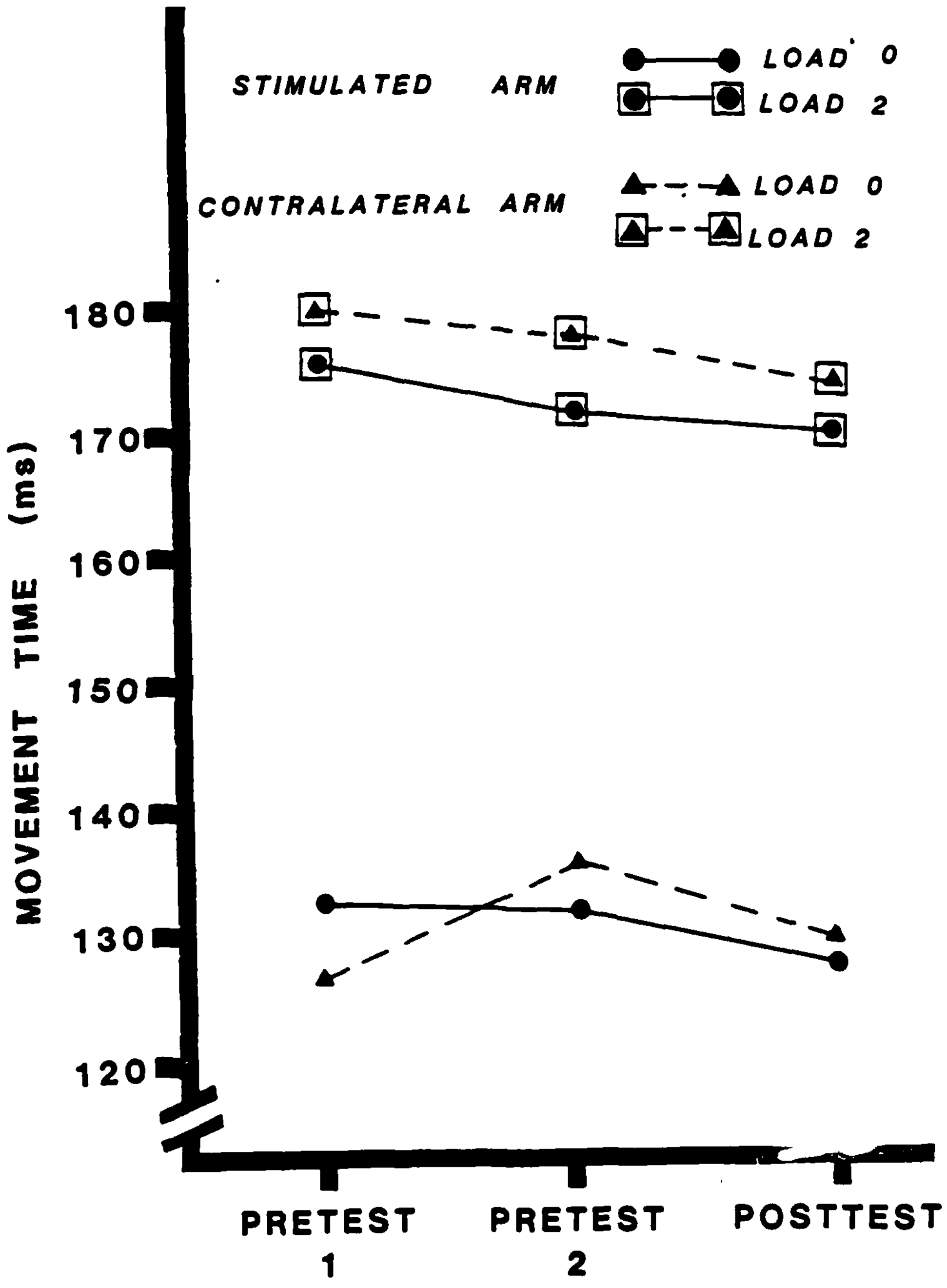

Figure 5. Male movement times for stimulated and contralateral arm flexion. Flexors were the stimulated muscles.

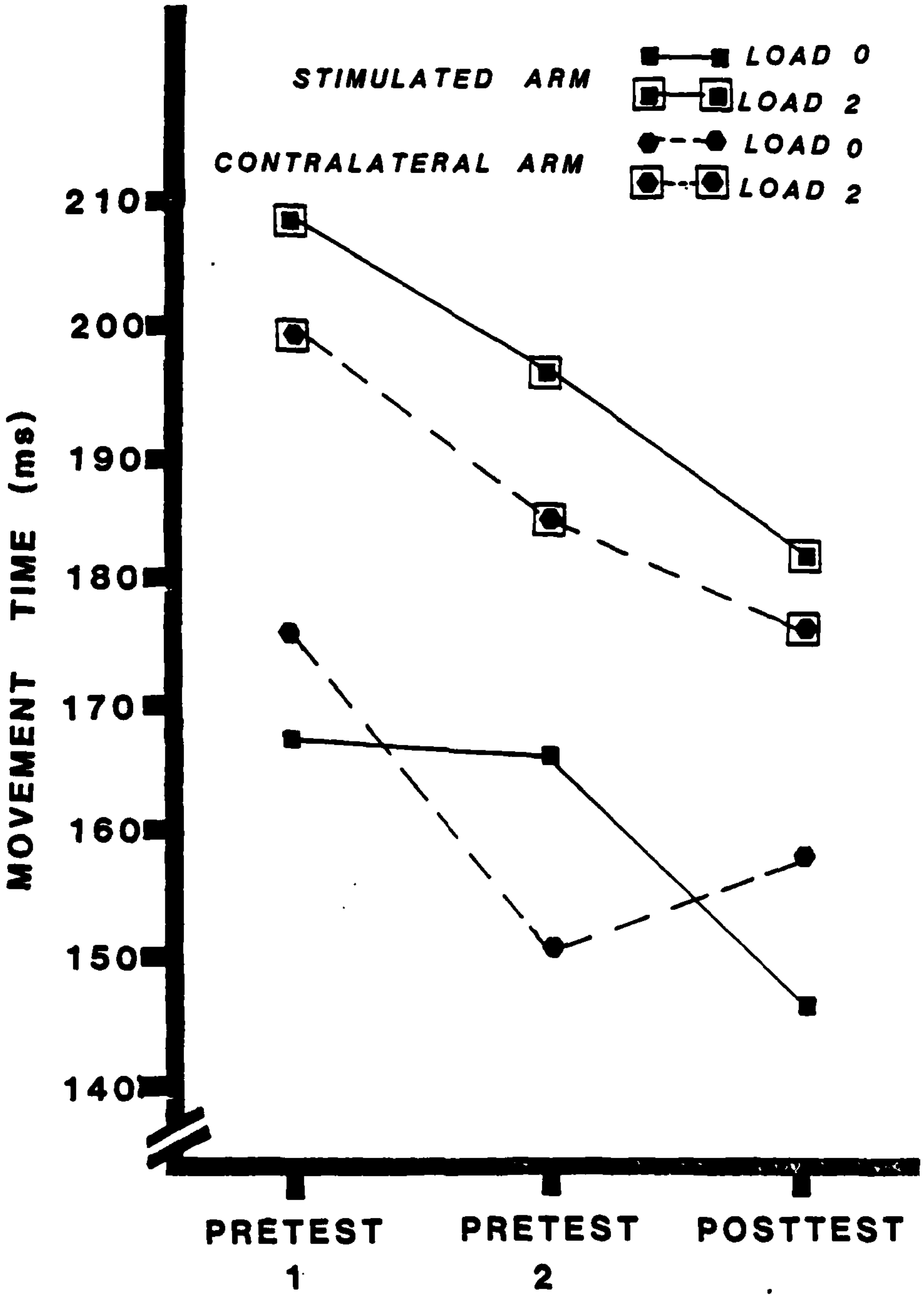

Figure 6. Male movement times for stimulated and contralateral arm extension. Flexors were the stimulated muscles.

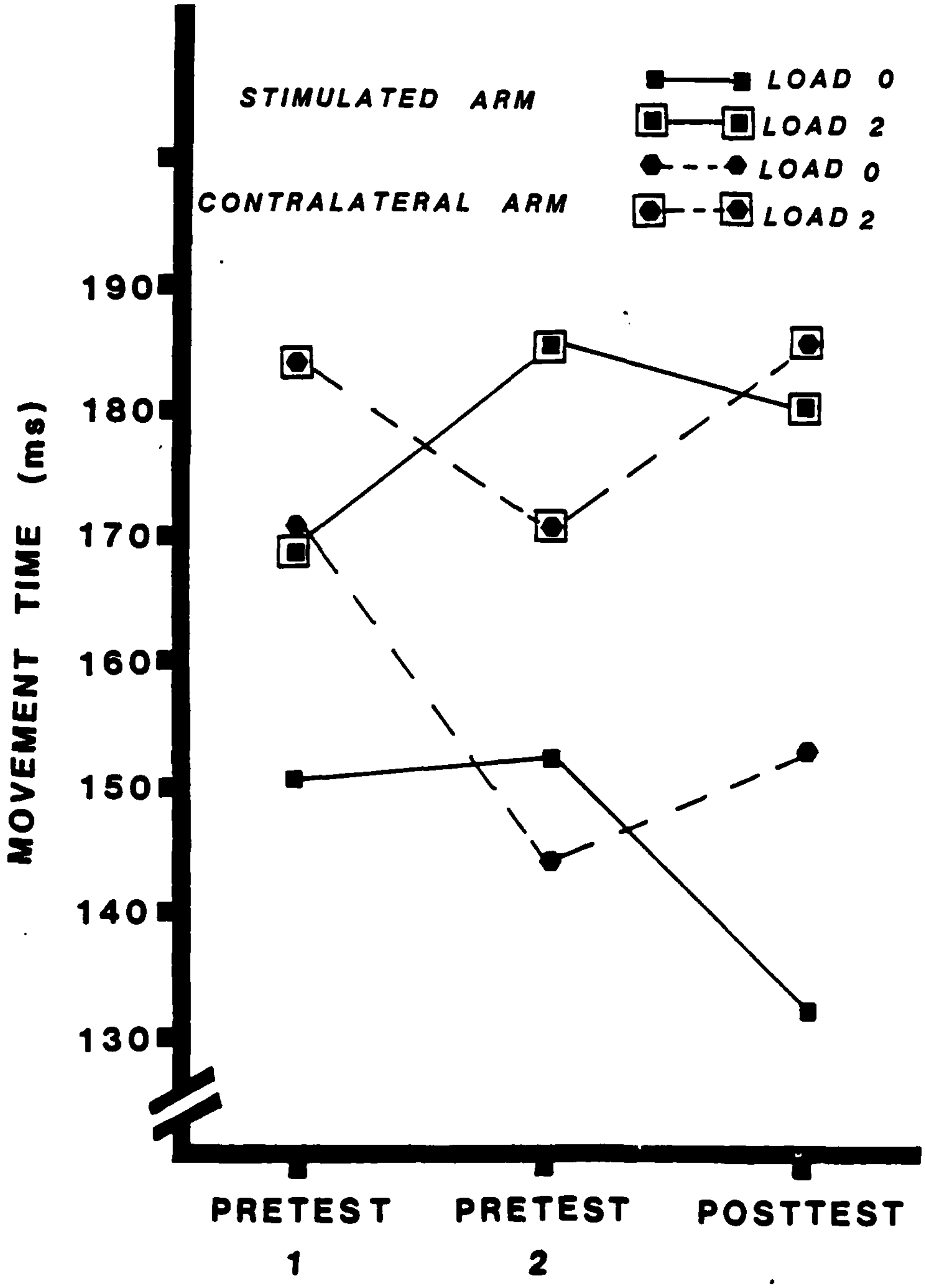

Figure 7. Male movement times for stimulated and contralateral arm extension. Extensors were the stimulated muscles.

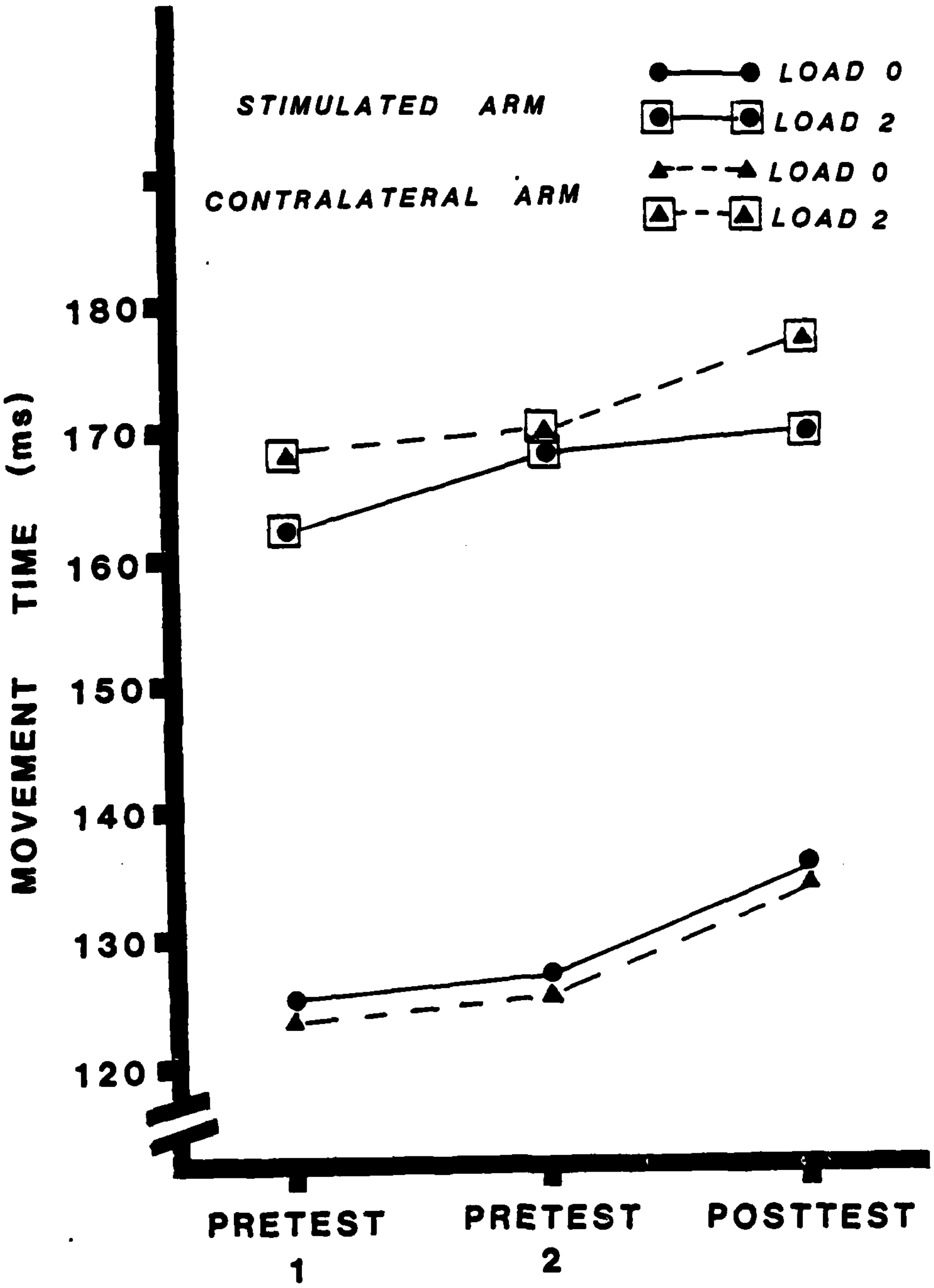

Figure 8. Male movement times for experimental and contralateral arm flexion. Extensors were the stimulated muscles.

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